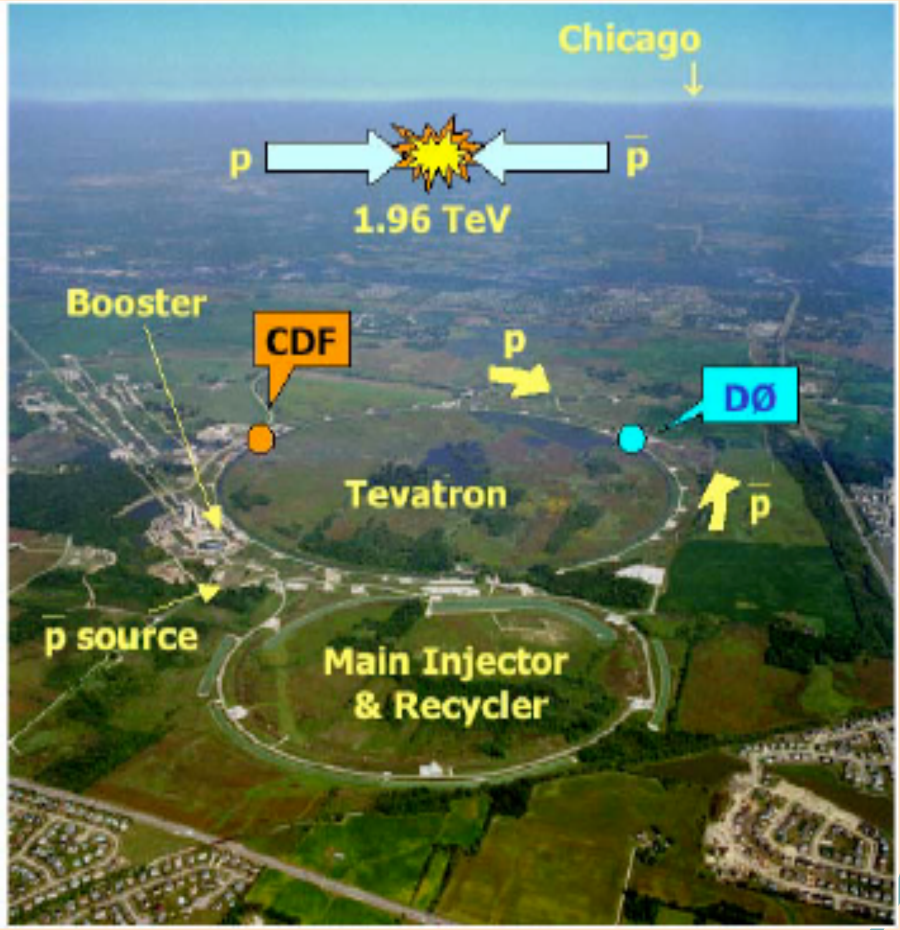
Top and Ewk Results from the Tevatron

Andrew Ivanov
University of California, Davis
for the CDF and DØ Collaborations

Hadron Structure
September, 2007

The Tevatron Collider

- Operating at presently world's highest particle energy collisions
- Currently the world's only top quark production machine
- Two multi-purpose detectors
- Run 1 (1992-1996)
  - $\sqrt{s}$ = 1.8 TeV
  - Integrated Lum ~110 pb^{-1}
  - Top Discovery!
- Run 2 (2001-present)
  - $\sqrt{s}$ = 1.96 TeV

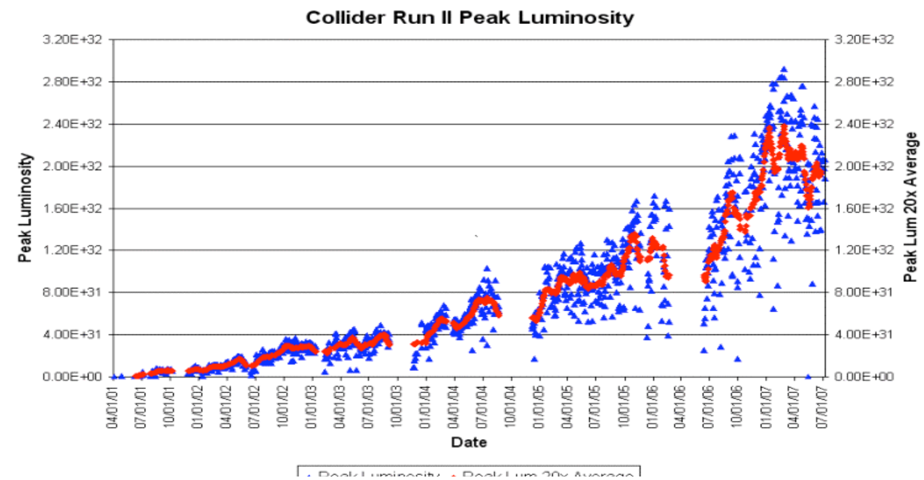


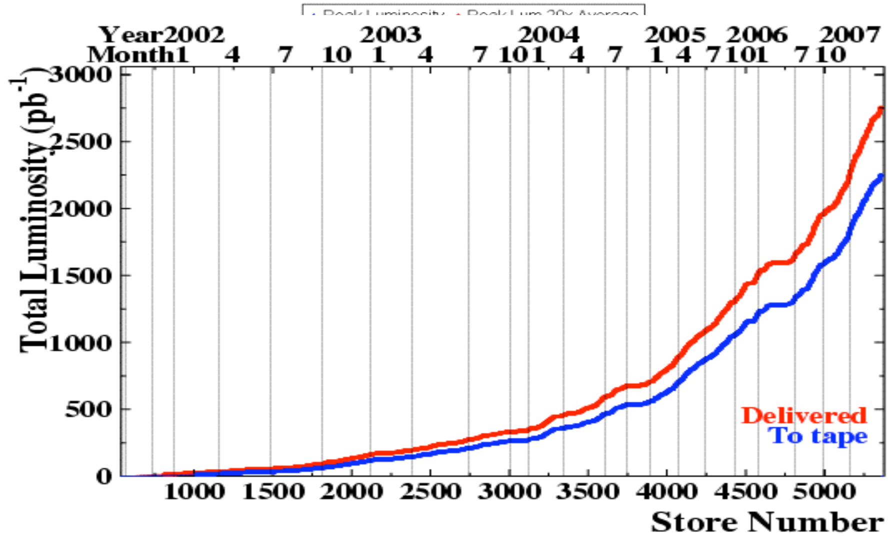
Tevatron Performance

- Record Initial Luminosity 2.9×10^{32} $cm^2 s^{-1}$
- Luminosities above 2×10^{32} $cm^{-2} s^{-1}$ are now common
- Expect initial luminosities above 3×10^{32} $cm^{-2} s^{-1}$ next year

- Integrated Luminosity per week ~ 50 pb-1 (a half of of the Run1 dataset)

- On tape ~ 2.7 fb^{-1}
- Aim for 6-8 fb^{-1} by 2009

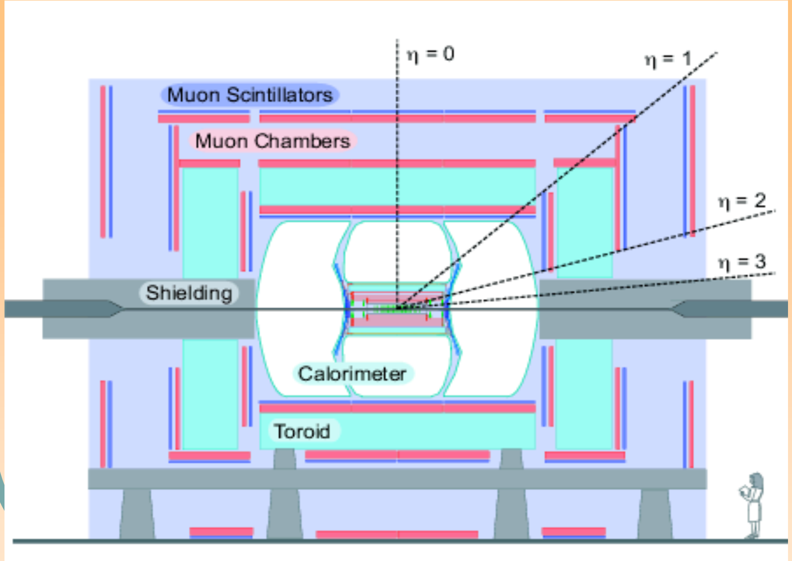


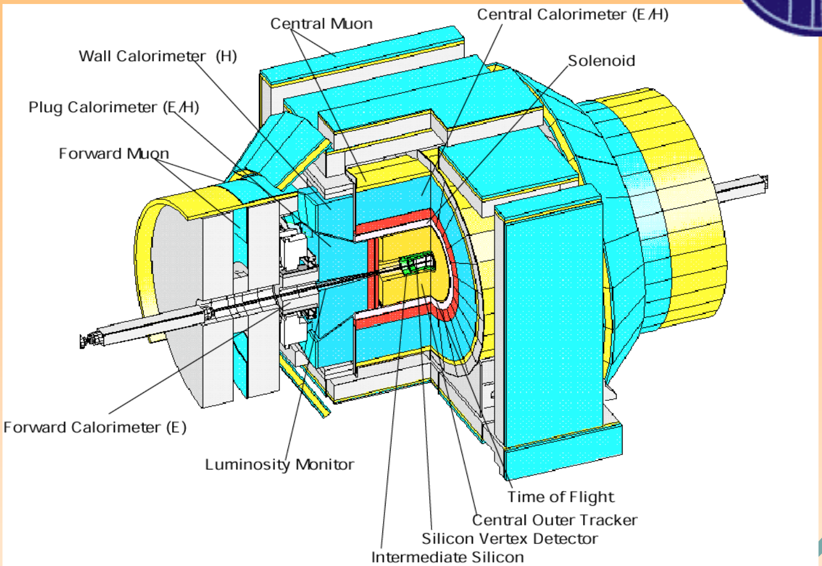


Tevatron Detectors

- Inner Silicon Precision Tracking
- Tracking Chambers
- Solenoid
- EM and HAD calorimeters
- Muon Detectors

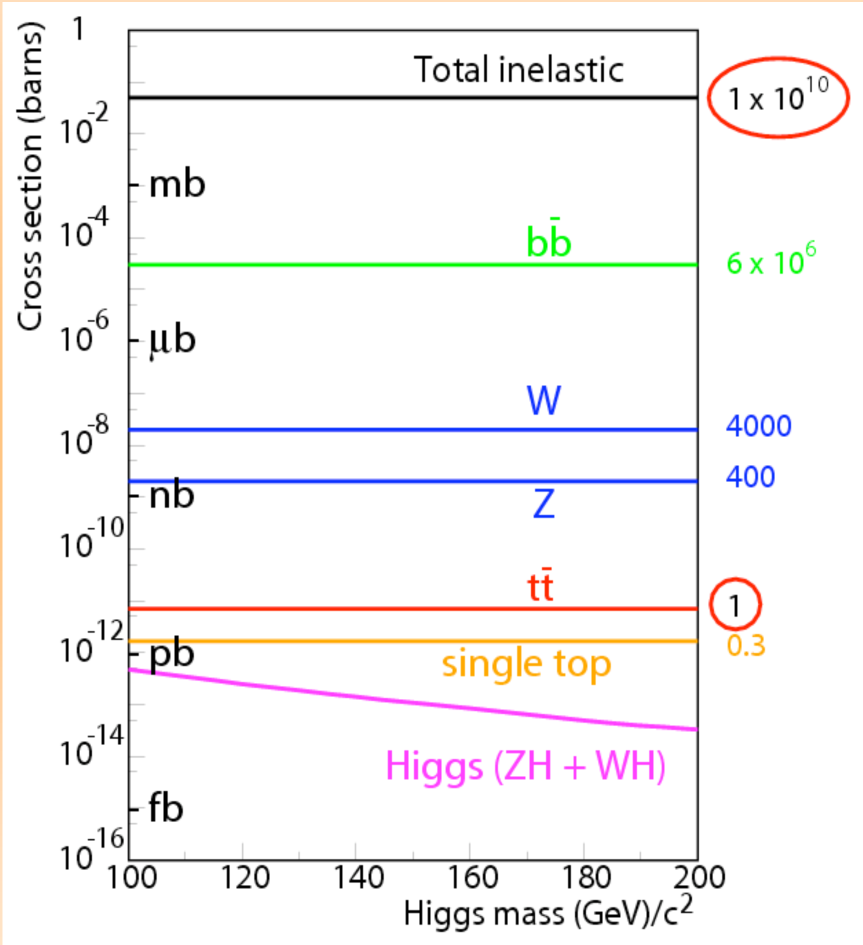
All crucial for ewk and top physics!



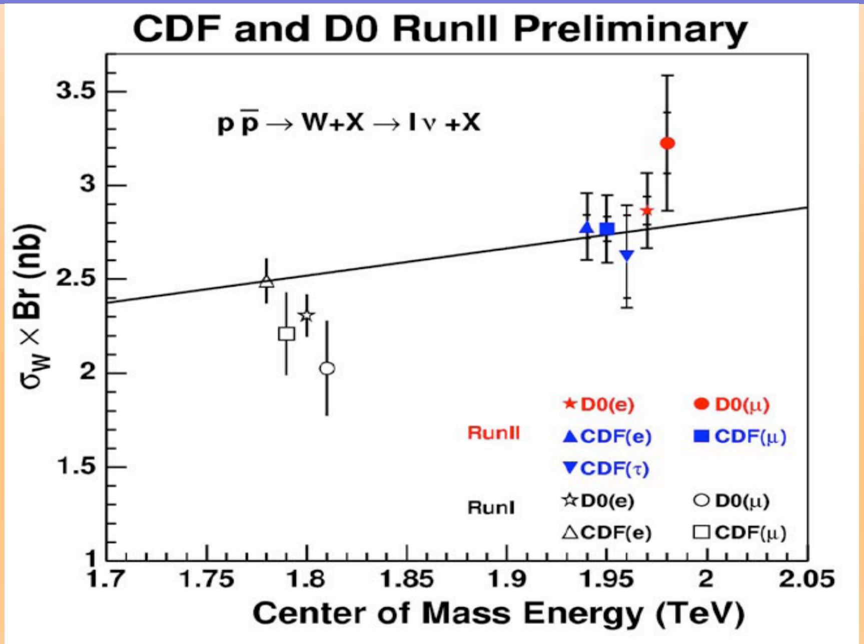


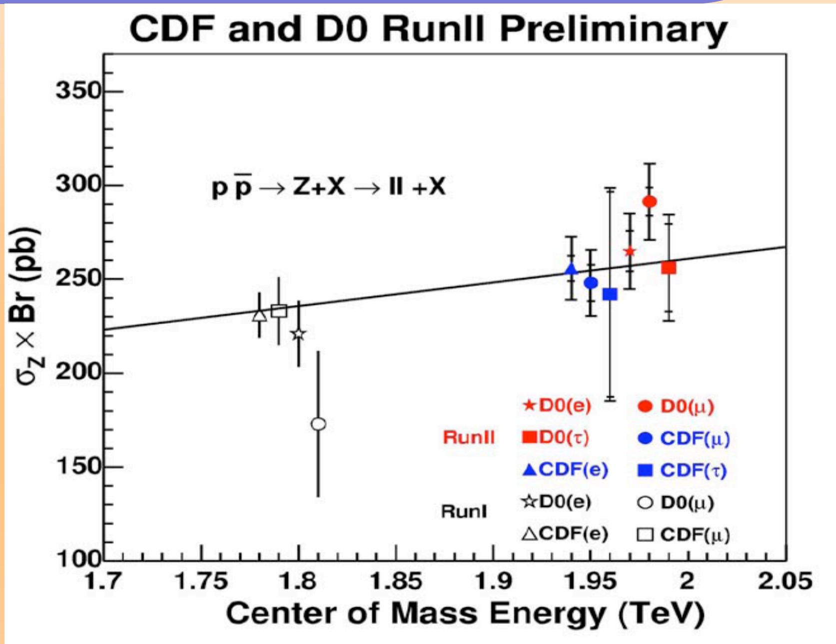
Production Cross Sections at Tevatron

- Cross sections for various physics processes vary over many orders of magnitude
- One top pair produced every 10^{10} inelastic collisions
- Physics processes of interest buried under heavy backgrounds
- Need good rejections factors, event selection, analysis strategy



Inclusive W/Z Cross Sections





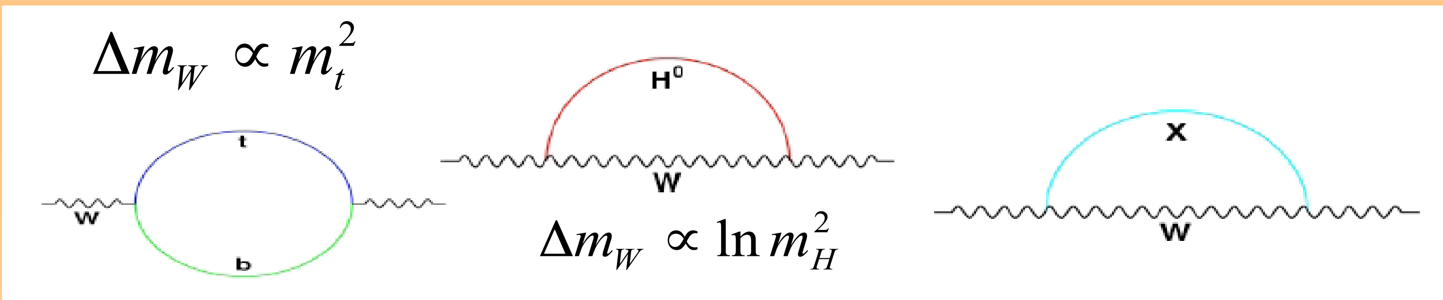
- Measured in all leptonic final states (W->eν, μν, τν; Z->ee, μμ, ττ)
- Good agreement with NNLO calculations (Stirling, Van Neereven)
- Measurements are dominated by luminosity uncertainty ~6% followed by PDF ~2%

W Mass

- W mass is a fundamental parameter of SM

$$m_W^{\,2} = \frac{\pi\alpha_{em}}{\sqrt{2}G_F \sin^2\theta_W (1-\Delta r)}$$

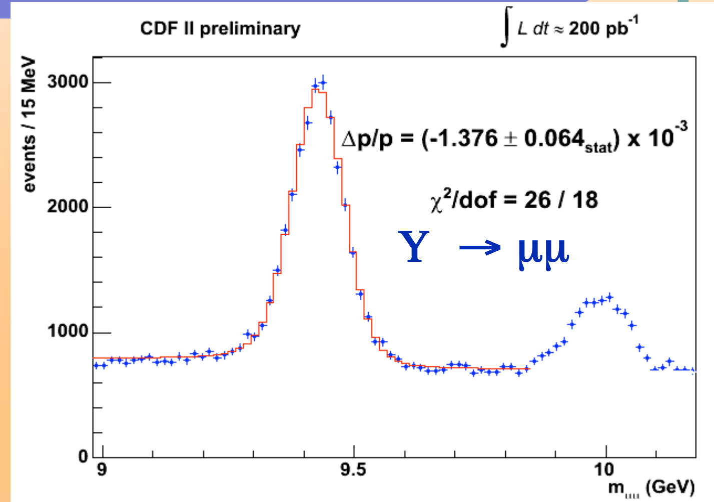
- Radiative corrections to M_W depend on M_{top} and M_{Higgs}
- W propagator includes H, tb, hypothetical new particle loops

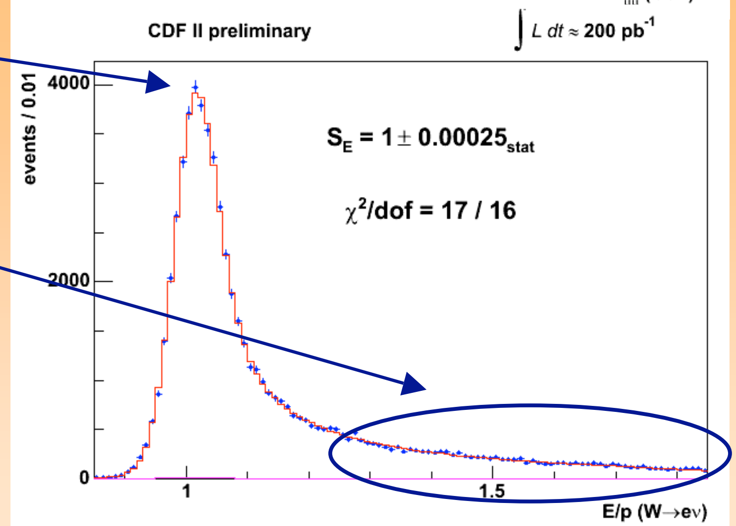


- Precise knowledge of M_W and M_{top} constrains M_{Higgs}
- With ultimate precision also sensitive to possible exotic radiative corrections

W Mass Measurement

- **Detector Calibration:**
  - Lepton Momentum Scale
    - Internal tracker alignment with cosmic rays
    - Curvature corrections from electron-positron E/P difference
    - Calibration with $J/\psi, \Upsilon \rightarrow \mu\mu$
    - Cross-check with $Z \rightarrow \mu\mu$
  - Lepton Energy Scale
    - Calibrated using E/p electron peak
    - Cross-checked with $Z \rightarrow ee$
  - Detector Material Model
    - Mapped energy loss and radiation lengths
    - Calibrated to data
  - Recoil Response
    - Calibrated with Z balancing
- W mass obtained from fits to lepton E_T, missing E_T and transverse mass distributions





W Mass Result

CDF II preliminary L = 200 pb^{-1}

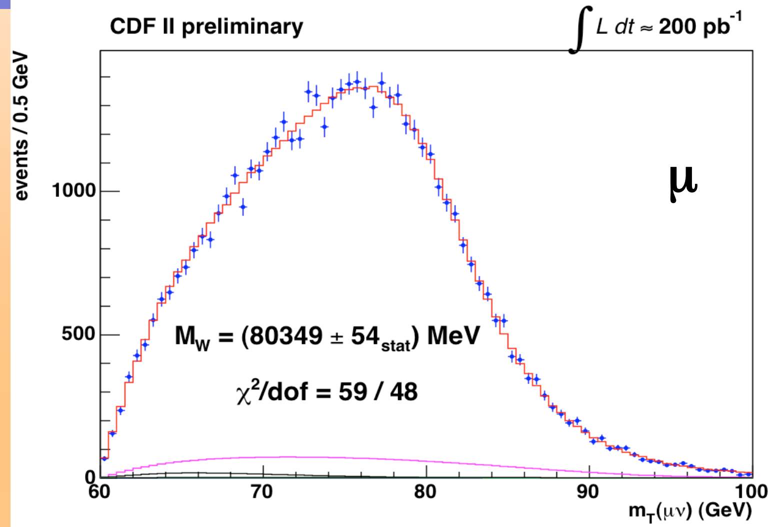
m_T Uncertainty [MeV]	Electrons	Muons	Common
Lepton Scale	30	17	17
Lepton Resolution	9	3	0
Recoil Scale	9	9	9
Recoil Resolution	7	7	7
$u_{\parallel}$ Efficiency	3	1	0
Lepton Removal	8	5	5
Backgrounds	8	9	0
$p_T(W)$	3	3	3
PDF	11	11	11
QED	11	12	11
Total Systematic	39	27	26
Statistical	48	54	0
Total	62	60	26

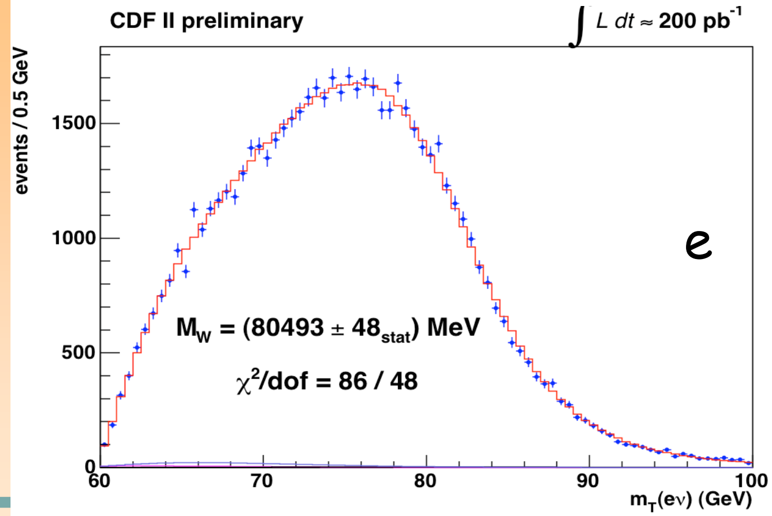
M_W = 80413 ± 48 MeV

80413 ± 34 (stat) ± 34 (syst)

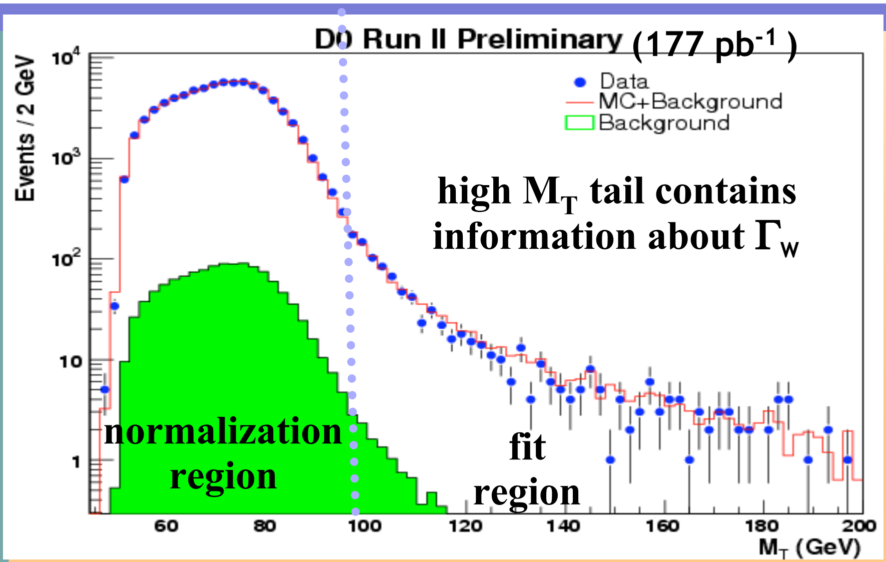
Single most precise measurement to date!

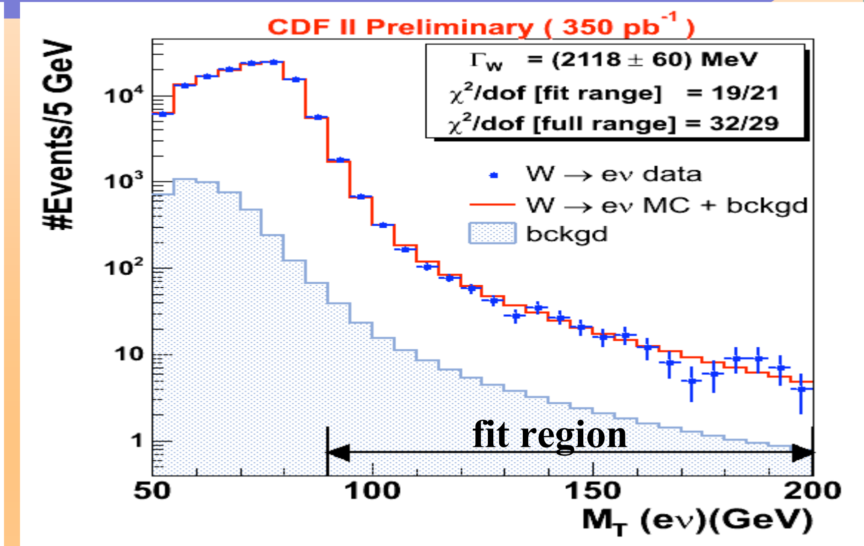
hep-ex/0707.0085





Direct Measurement of Γ_W





Γ_W [DØ(e)] = 2011 ± 142 MeV

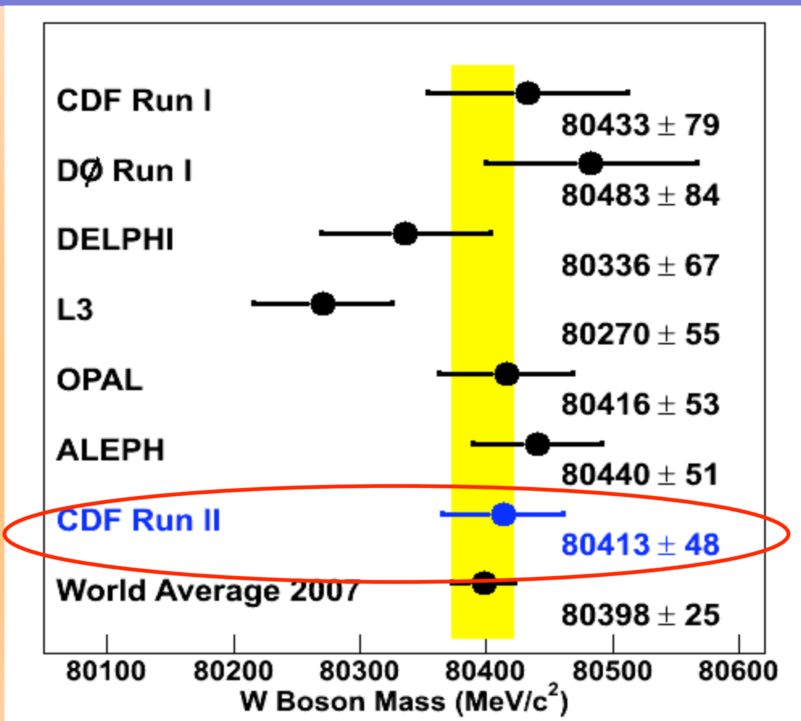
Γ_W [CDF(e+μ)] = 2032 ± 71 MeV

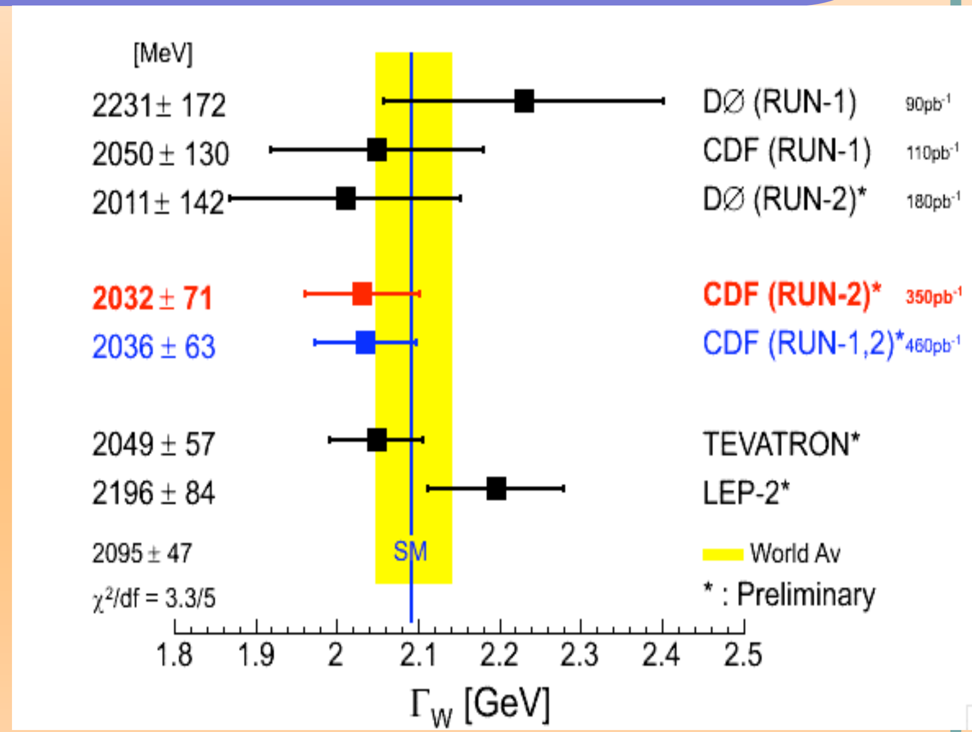
CDF's Result is the world's most precise single direct measurement!

CDF Run II Preliminary (350 pb^{-1})

	$\Delta\Gamma_W$ [MeV]		
	Electrons	Muons	Common
Lepton Scale	21	17	12
Lepton Resolution	31	26	0
Simulation	13	0	0
Recoil	54	49	0
Lepton ID	10	7	0
Backgrounds	32	33	0
$p_T(W)$	7	7	7
PDF	16	17	16
QED	8	1	1
W mass	9	9	9
Total systematic	78	70	23
Statistical	60	67	0
Total	98	97	23

M_W and Γ_W World Averages





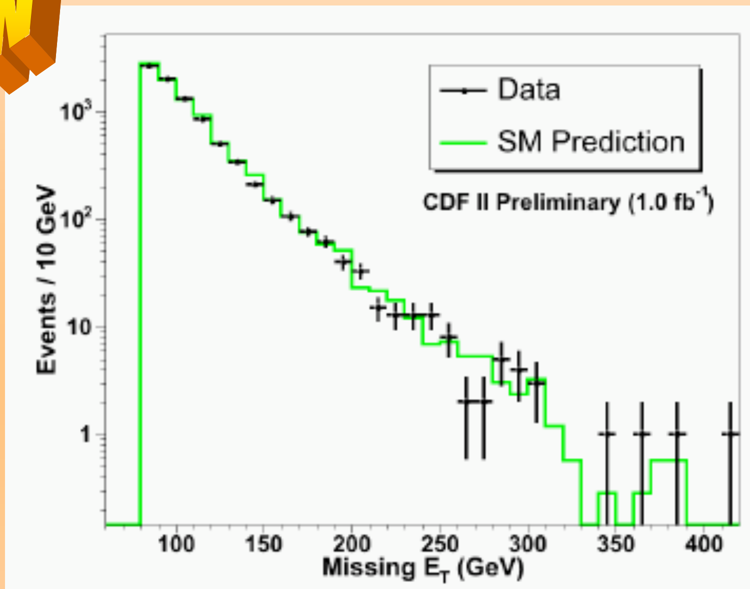
With new CDF's most precise single results:

M_W : 80392 -> 80398 MeV **Γ_W : 2139 -> 2095 MeV**

ΔM_W : 29 -> 25 MeV **$\Delta\Gamma_W$: 60 -> 47 MeV**

Z Boson Invisible Width

New



- Interepret the result of no excess in "monojet" + large missing ET extra dimensions search

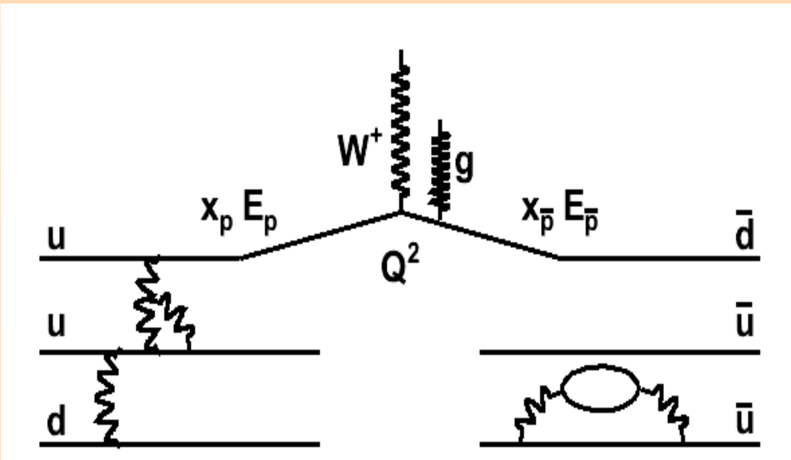
$$\Gamma_Z(\text{inv}) = \frac{\sigma(Z+1\text{jet})\,x\,Br(Z\to\nu\nu)}{\sigma(Z+1\text{jet})\,x\,Br(Z\to ll)}\ x\ \Gamma_Z(ll)$$

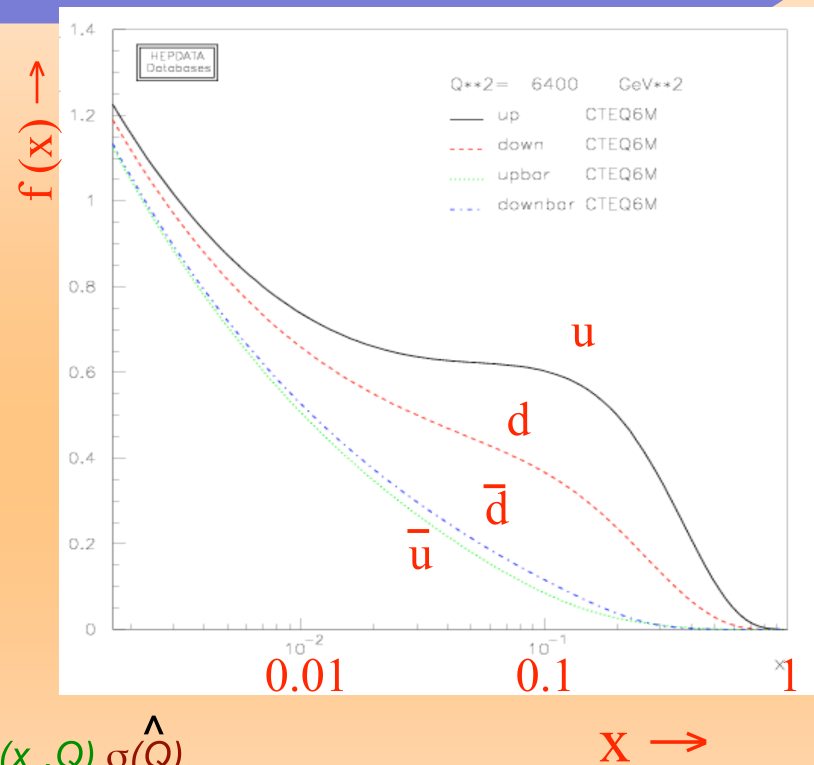
LEP

$\Gamma_{Z\ inv.}$ = 466 ± 42 MeV

Experiment	Γ(Z -> invisible) [MeV]
CDF	466 +/- 42
L3	498 +/- 17
OPAL	539 +/- 31
ALEPH	450 +/- 48
LEP Combined	503 +/- 16
LEP Indirect	499.0 +/- 1.5

QCD Boson Production and Parton Distribution Functions





$$\sigma = \sum_{ab} \int dQ\, \delta(Q - 2E_p\sqrt{x_p x_{\bar{p}}}) \int dx_p\, f_a(x_p, Q) \int dx_{\bar{p}}\, f_b(x_{\bar{p}}, Q)\, \hat{\sigma}(Q)$$

Sum over quarks, gluons

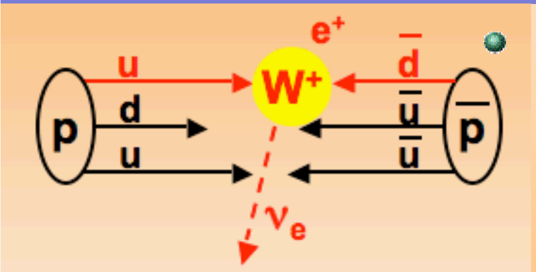
Kinematic constraint

Parton distribution functions

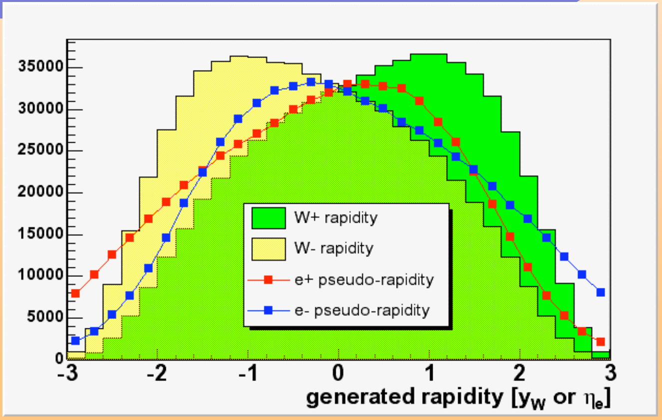
Calculable hard scattering cross section

- Parton momentum fraction within the proton depends on quark type and is different for valence and sea quarks

W Charge Asymmetry

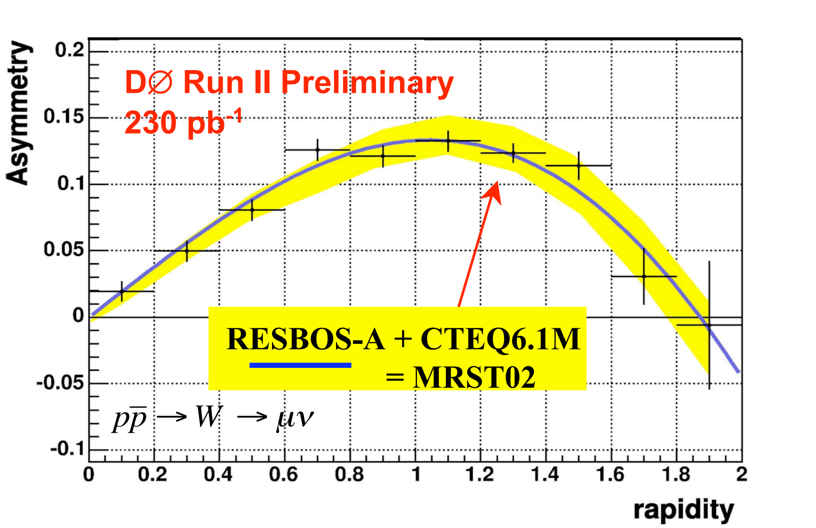


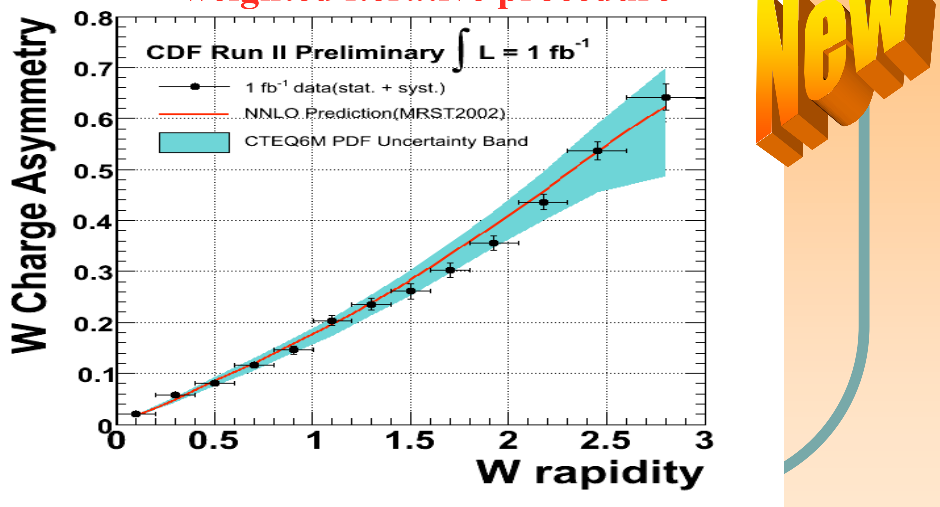
- W boson exhibit a production asymmetry due to the different PDF of u and d quarks in the proton



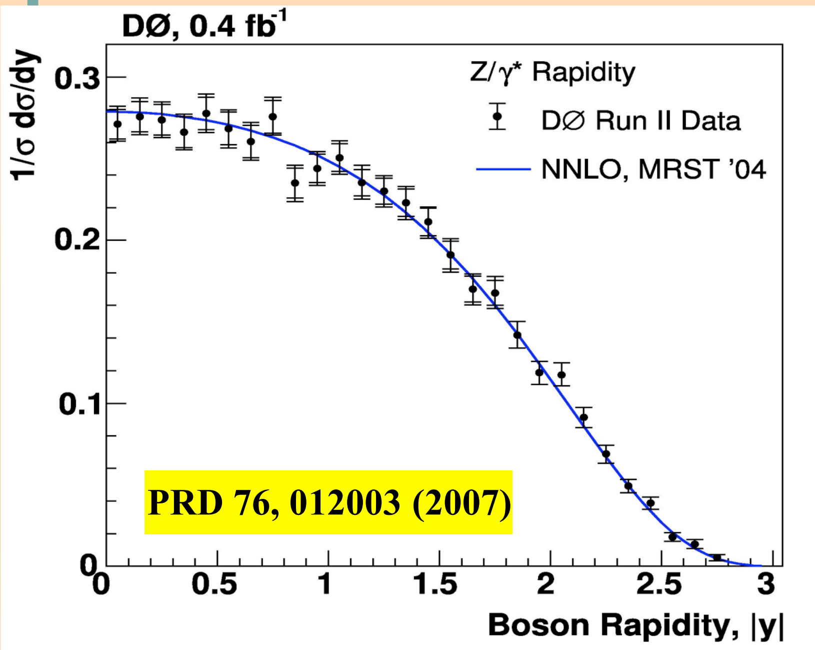
- Measure a lepton charge asymmetry, use the W mass constraint, weigh solutions based on
  - W production mechanism ($d\sigma/dy$)
  - V-A structure of W decay $(1\pm\cos\theta^*)^2$

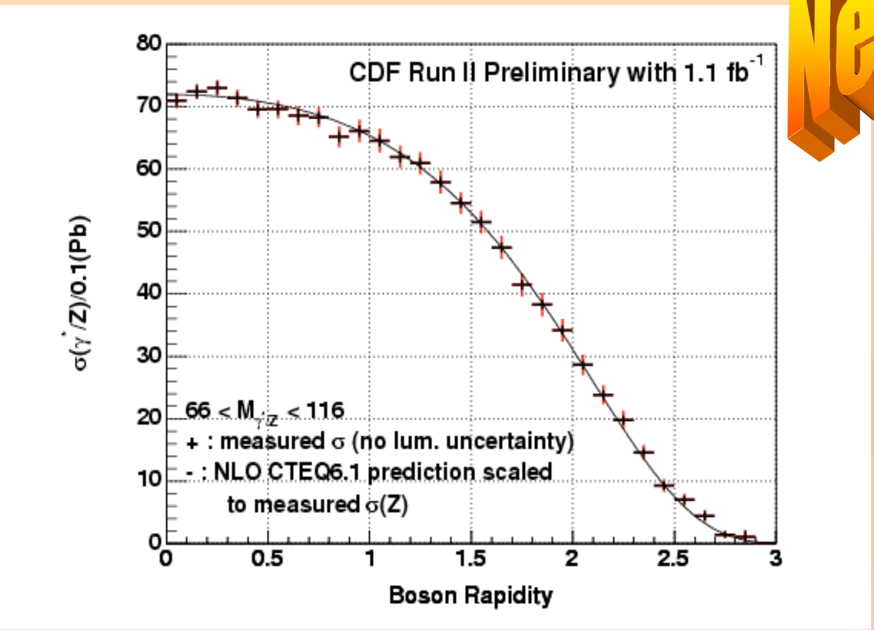
CDF significantly increases sensitivity to PDF by reconstructing W rapidity directly with a weighted iterative procedure





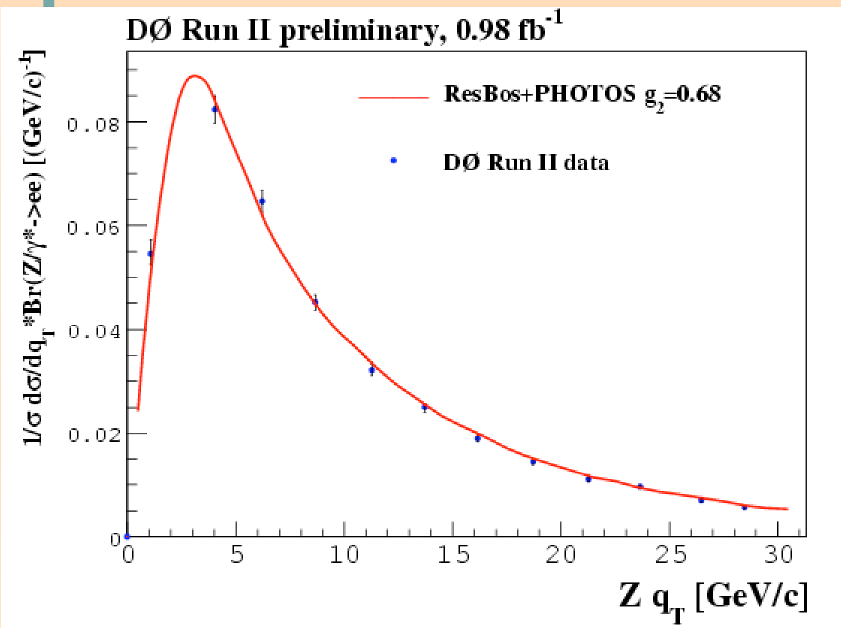
Drell-Yan $Z/\gamma^* \to e^+e^-$ $d\sigma/dy$ Differential Cross Section

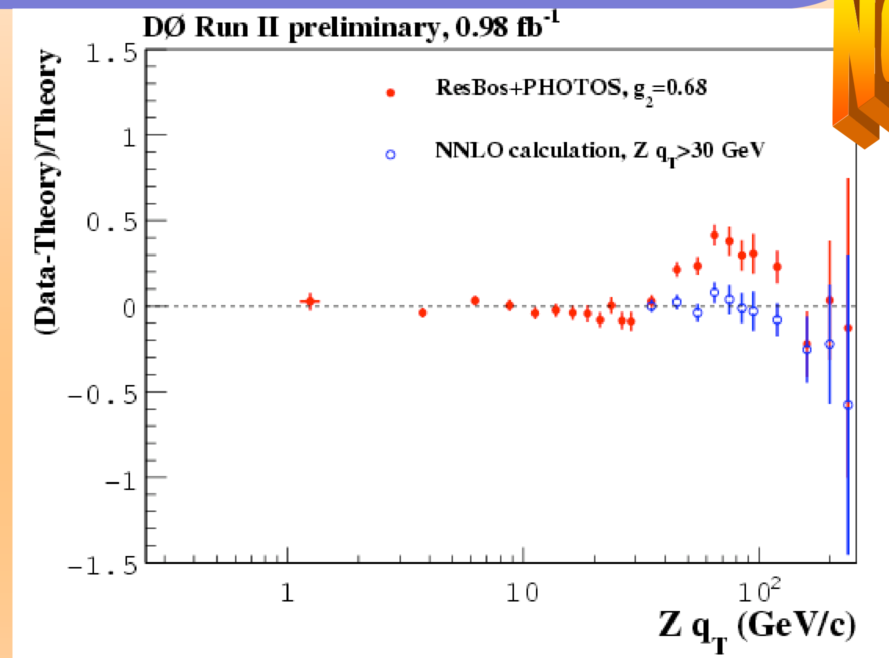




- Measurement probes the small x, high Q^2 portion of the PDFs
- Good agreement with theory
- Measurement can be used to constrain PDFs.

Drell-Yan $Z/\gamma^* \to e^+e^-$
$d\sigma/dq_T$ Differential Cross Section



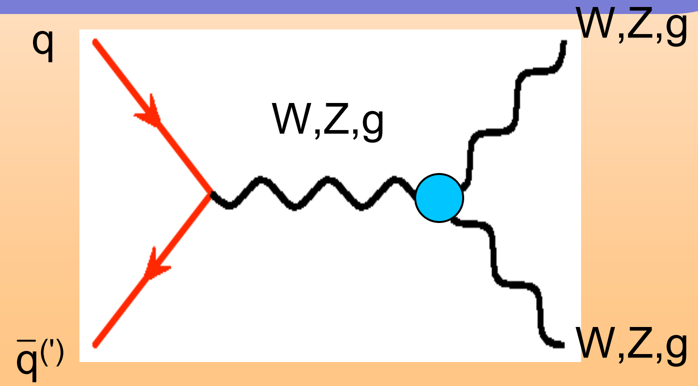


- At high-q_T (> 20 GeV) dominated by radiation of a single parton described by perturbative QCD (NNLO)
- At low-q_T reliably predicted by soft gluon resummation (CSS)
- The parametrization of Z boson q_T spectrum used to reduce uncertainties in the W mass measurement

J. Collins, D. Soper, G. Streman, Nucl. Phys. B250 (1985) 199

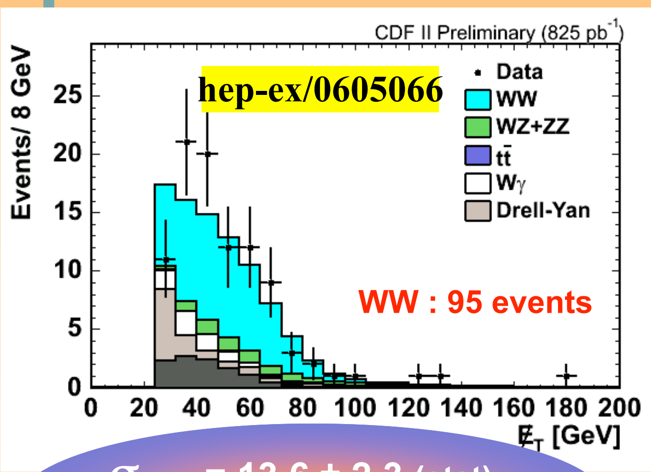
Dibosons / WW Production

- Probe non-Abelian nature of $SU(2)_L \otimes U(1)_Y$ via gauge boson self-interactions (triple, quartic)
- The Tevatron (ppbar) is sensitive to different combinations of tri-linear gauge couplings than LEP (e^+e^-) and explores higher s
- Intermediate step towards SM Higgs searches



$$q\bar{q}' \to W^* \to W\gamma \ : WW\gamma \text{ only}$$
$$q\bar{q}' \to W^* \to WZ \ : WWZ \text{ only}$$
$$q\bar{q} \to Z/\gamma^* \to WW \ : WW\gamma \, , WWZ$$
$$q\bar{q} \to Z/\gamma^* \to Z\gamma \ : \boxed{ZZ\gamma \, , Z\gamma\gamma}$$
$$q\bar{q} \to Z/\gamma^* \to ZZ \ : \boxed{ZZ\gamma \, , ZZZ}$$

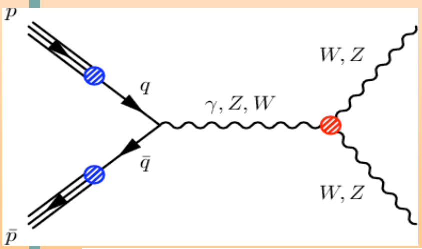
Absent in SM



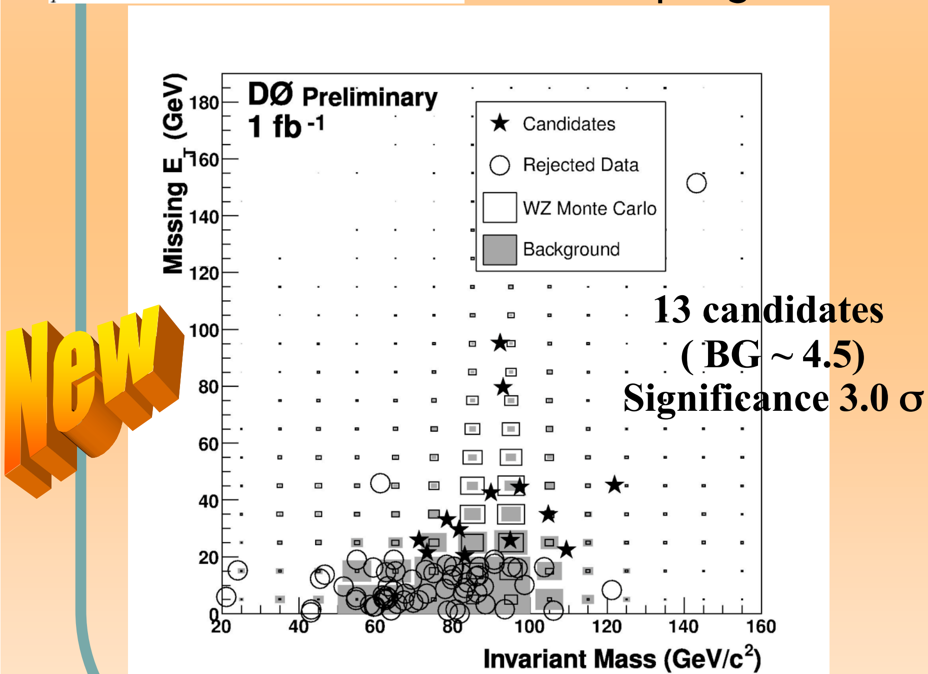
σ_{WW} = 13.6 ± 2.3 (stat) ± 1.6 (syst) ± 1.2 (lumi) pb

In good agreement with NLO theory: 12.4 ± 0.8 pb

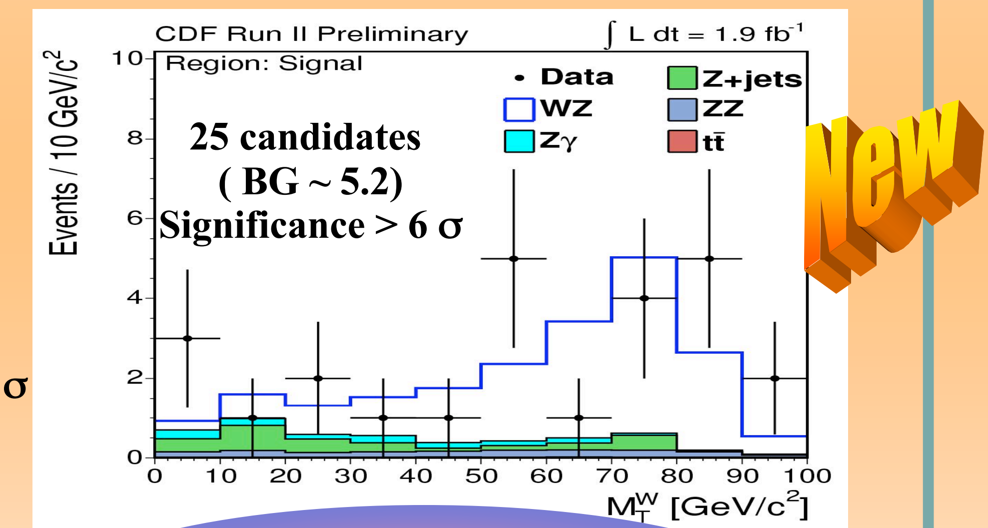
WZ Production



- s-channel provides sensitivity to WWZ vertex coupling
- CDF: Increased sensitivity due to significant improvement in lepton acceptance
- DØ: Use Z p_T distribution to set tightest limits on anomalous couplings



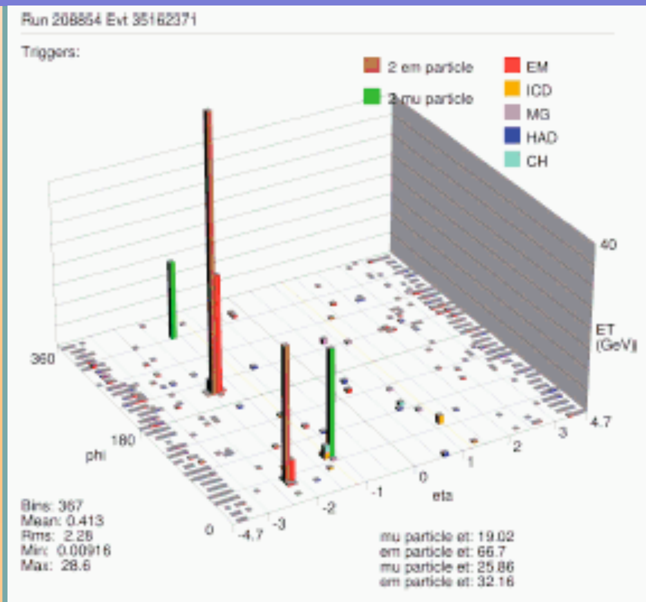
$\sigma_{WZ} = 2.7\ ^{+1.7}_{-1.5}$ pb



$\sigma_{WZ} = 4.3\ ^{+1.3}_{-1.0}$ (stat) $\pm$ 0.2 (syst) $\pm$ 0.3 (lumi) pb

In good agreement with NLO theory: 3.7 ± 0.3 pb

First hints of ZZ



- NLO: σ = 1.6 ± 0.1 pb

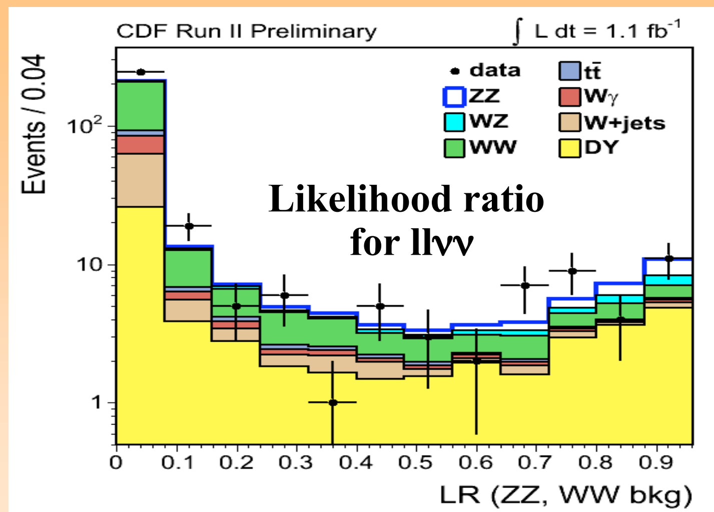
J. M. Campbell R. K. Ellis PRD60 (1999)

- DØ: 1 ee$\mu\mu$ candidate, expected ~ 1.5:

σ(ZZ) < 4.3 pb (95%CL)

- CDF combined 4l and ll$\nu\nu$ channels:
  - CDF: Observed 1 ee$\mu\mu$ candidate; expect ~2.5
  - Significance > 3 σ

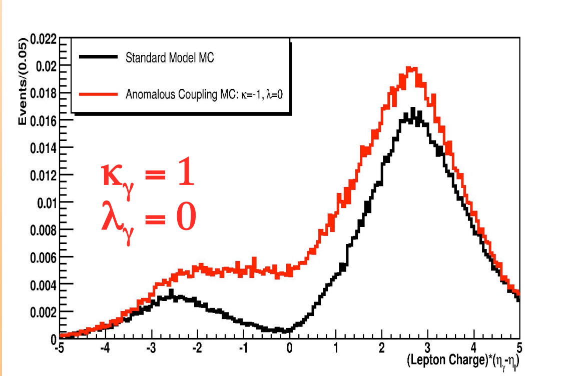
$\sigma(ZZ) = 0.75^{+0.71}_{-0.54}$ pb

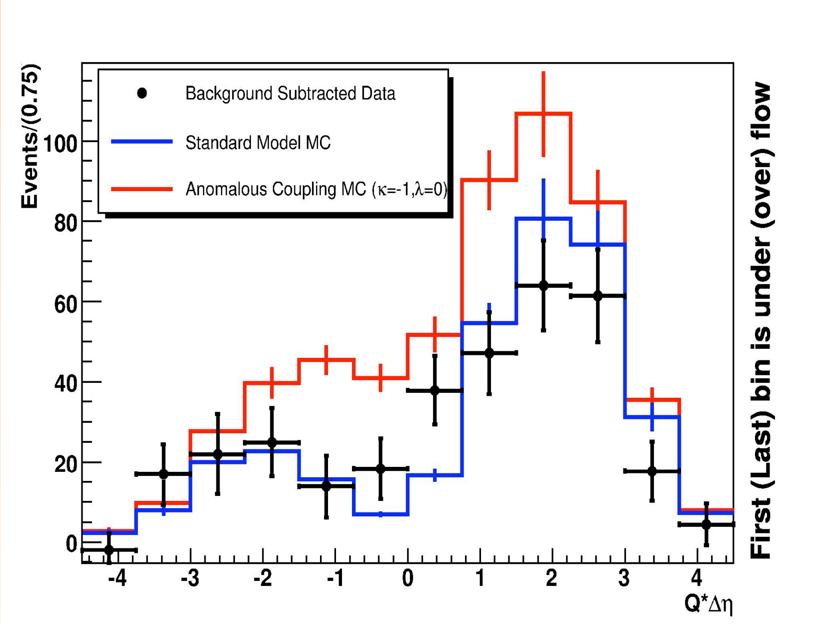


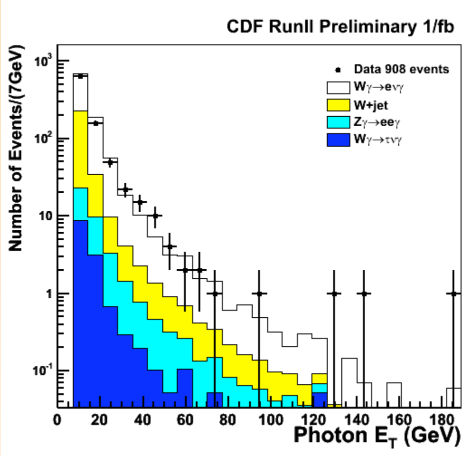
Wγ Production

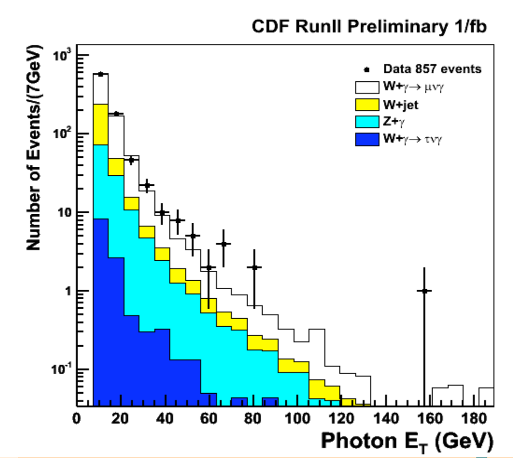
- DØ: Radiation Amplitude Zero
- Due to interference of tree-level diagrams the angle between W and incoming quark is

  $\cos(\theta^*) = -(1+2Q_d) = +/- 1/3$
- Measure a dip in η_{lepton}
- In the alternative model a set of anomalous WWγ couplings produces a zero magnetic dipole moment for W







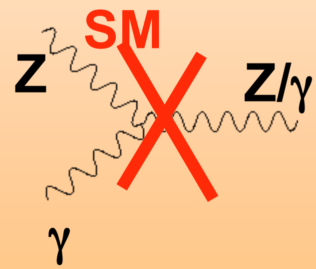


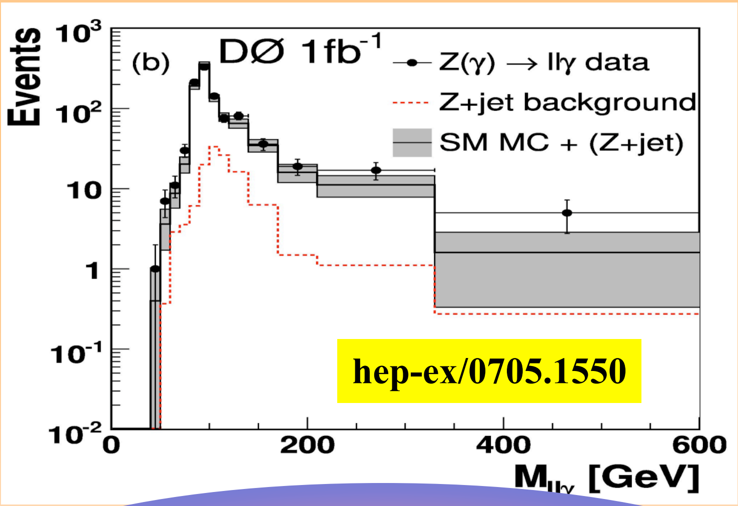
$\sigma[\text{CDF}]_{W\gamma}$ = 18.0 ± 2.8 pb

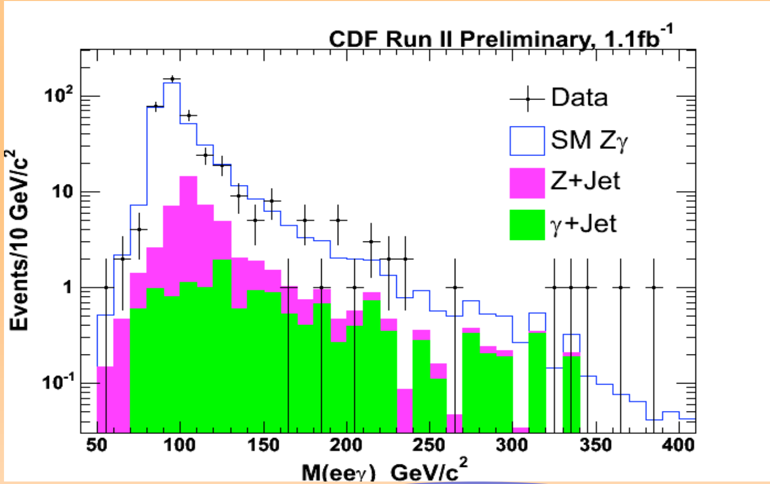
($E_{T,\gamma}$ > 7 GeV, $\Delta R_{(l,\gamma)}$ > 0.7)

Zγ Production

- SM: No Triple Gauge Coupling at tree level
- DØ: Set tightest limits on Zγ anomalous couplings
- h_{40} limits surpass LEP





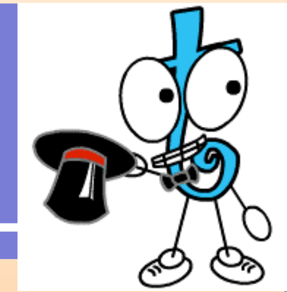


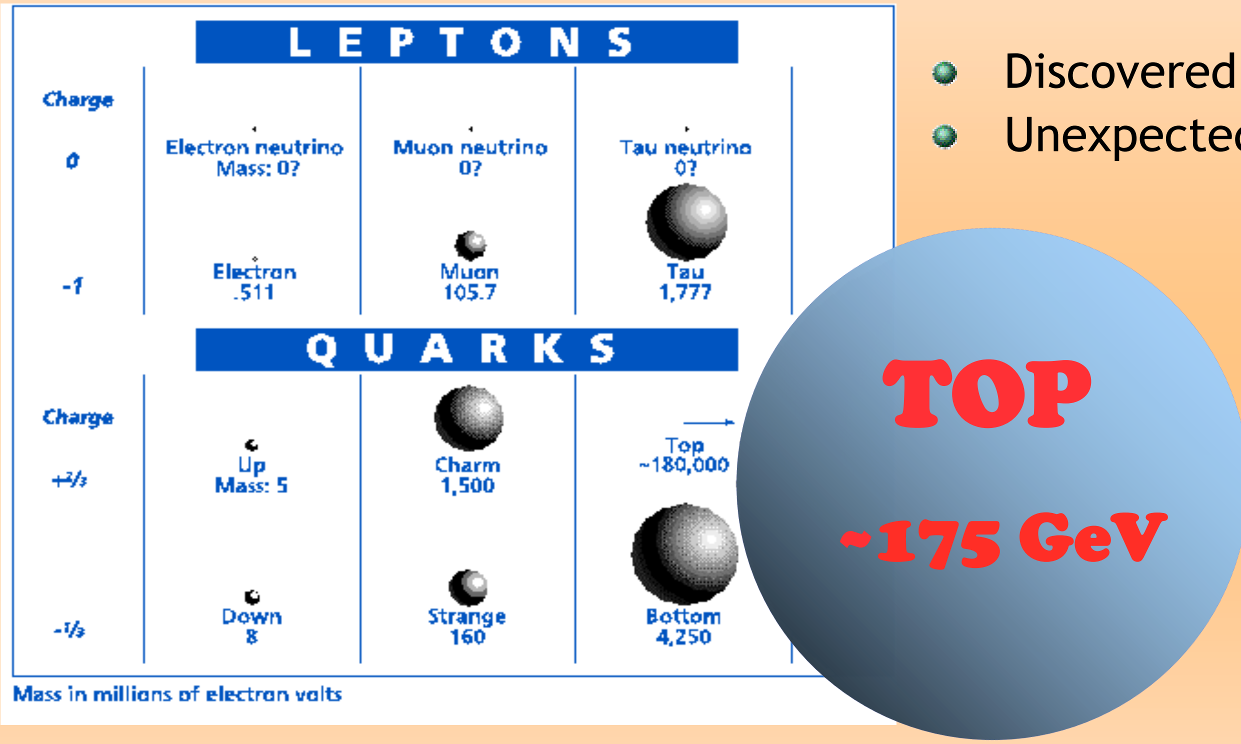
$\sigma_{Z\gamma}$ = 4.96 ± 0.3 ± 0.3 (lumi) pb
($E_{T,\gamma}$ > 7 GeV, $\Delta R_{(l,\gamma)}$ > 0.7, M_{ll} > 30 GeV)

$\sigma_{Z\gamma}$ = 4.9 ± 0.5 pb
($E_{T,\gamma}$ > 7 GeV, $\Delta R_{(l,\gamma)}$ > 0.7, $M_{ee\gamma}$ > 40 GeV)

In good agreement with theory: 4.7 ± 0.4 pb

Top quark





- Discovered in 1995 at Tevatron
- Unexpectedly huge mass

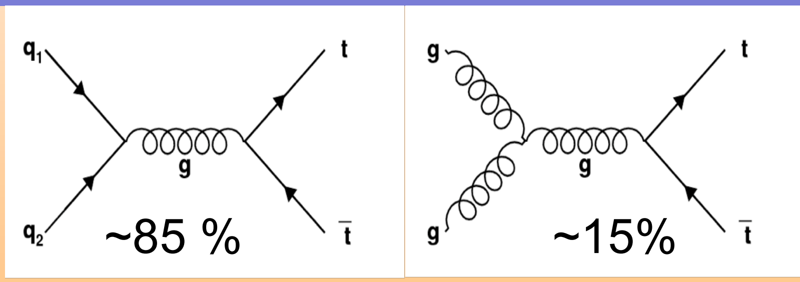
$$y_t = \frac{\sqrt{2} m_t}{v} \approx 1$$

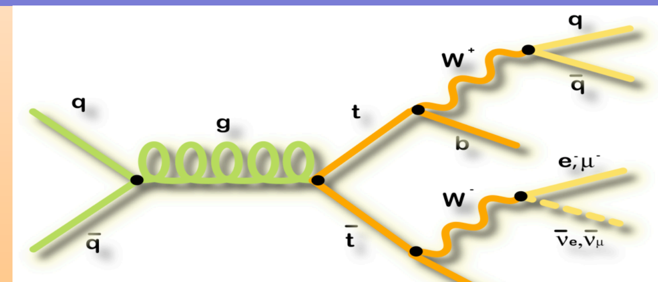
- Special role in the dynamics of EWSB ?
- Serves as a probe of BSM physics

$$\tau_{\text{top}} \sim 10^{-24}\,\text{s}\,,\ \Gamma^{-1} \approx (1.5\ \text{GeV})^{-1} \ll \Lambda^{-1}_{\text{QCD}} \sim (200\ \text{MeV})^{-1}$$

- Decays before hadronizing
- Passes momentum and spin info to its decay products

Top Quark Pair Production and Decay





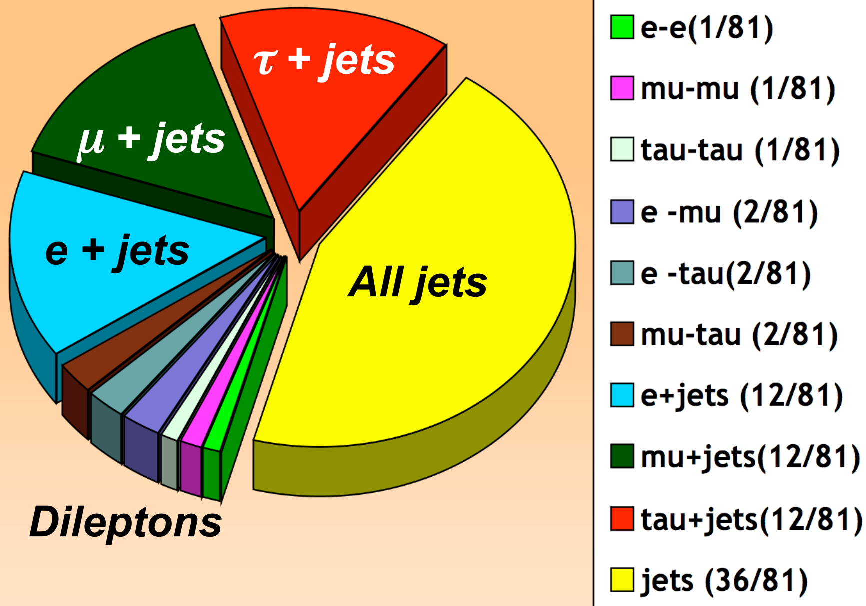
BR(t ->Wb) ~ 100%

NLO:

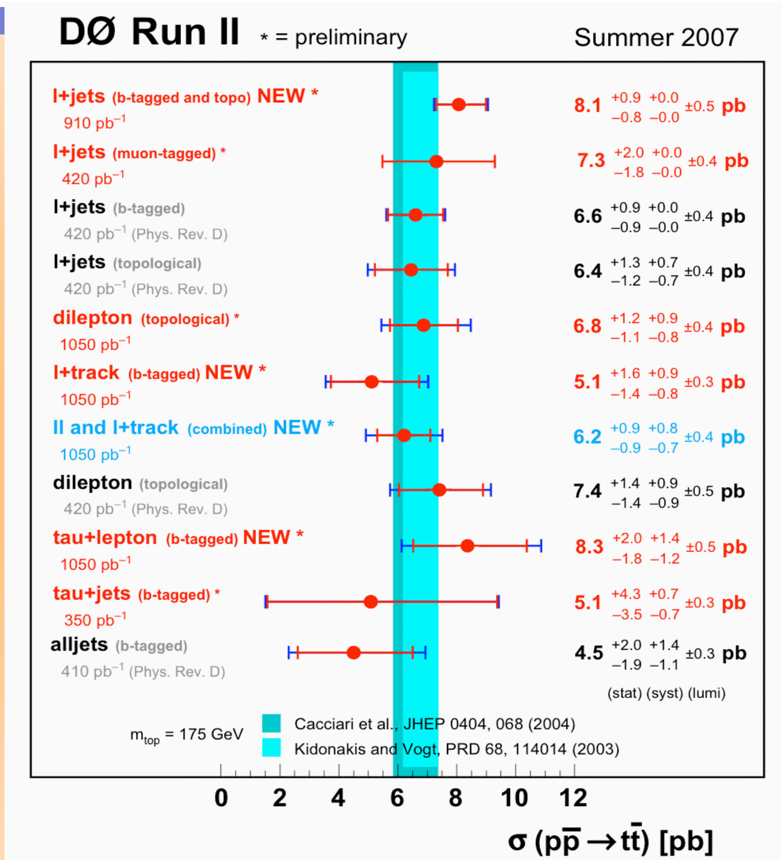
- $\sigma_{tt} = 6.7 \pm^{0.7}_{0.9}$ pb @ m_{top} = 175 GeV

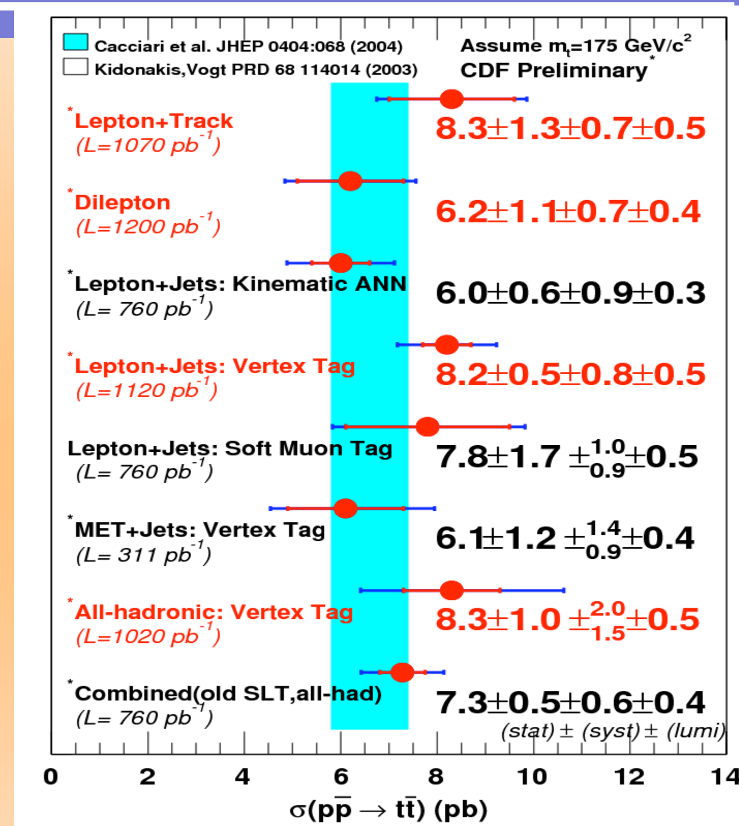
Cacciari et al. JHEP 0404:068(2004)
Kidonakis,Vogt PRD 68 114014(2003)

- *Event Classification (by W decay)*
  - *"Lepton [e,μ] + jets" (30%)*
    - ***$tt \rightarrow bl\nu bqq'$***
  - *"Dilepton [e,μ]" (5%)*
    - ***$tt \rightarrow bl\nu bl\nu$***
  - *"All jets" (44%)*
    - ***$tt \rightarrow bqq'bqq'$***
  - ***"Tau + X" (21%)***



σ_{tt} Measurements

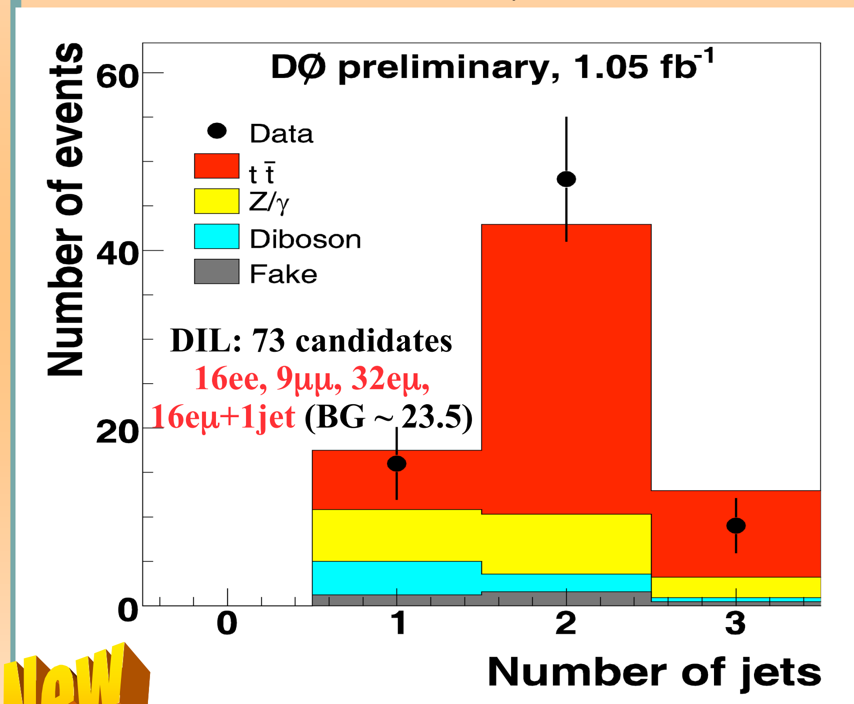


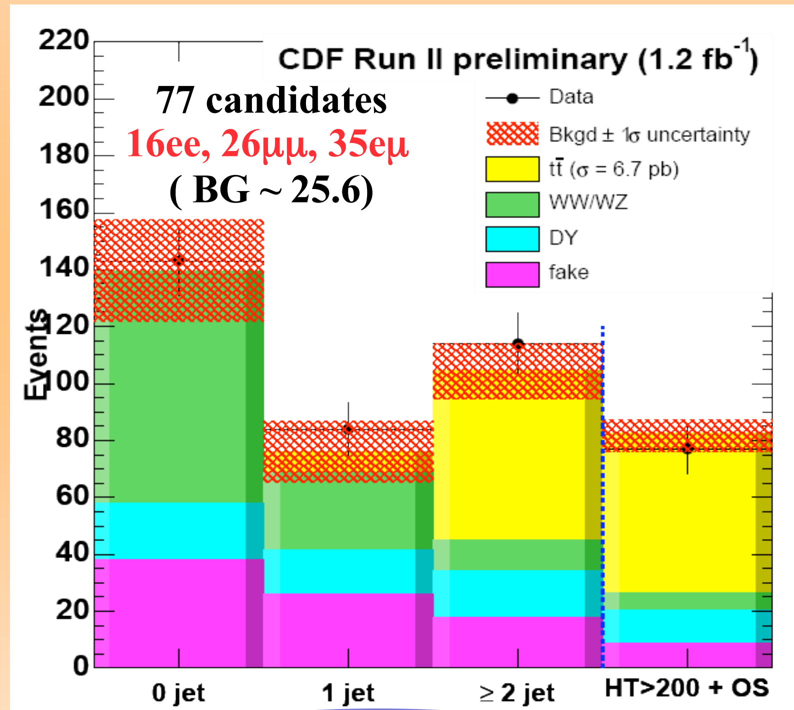


- Important indirect test of top quark properties
- Testing non-standard model top production mechanisms
- Top sample might contain an admixture of exotic processes

Cross Section in Dilepton channel

- Signature: high-P_T ee, $\mu\mu$, eμ, missing E_T, ≥ 2 jets
- DØ: ≥ 1 jet in eμ channel, measurement combined with l+track





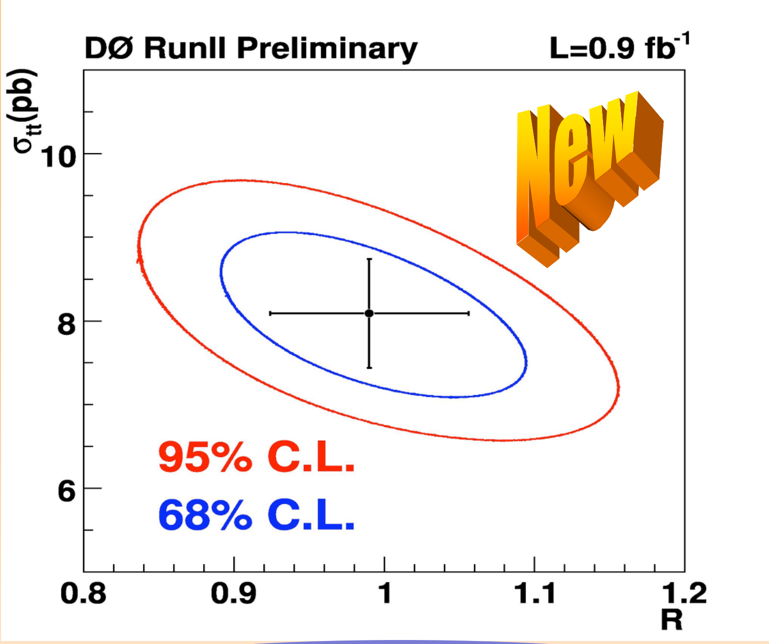
New

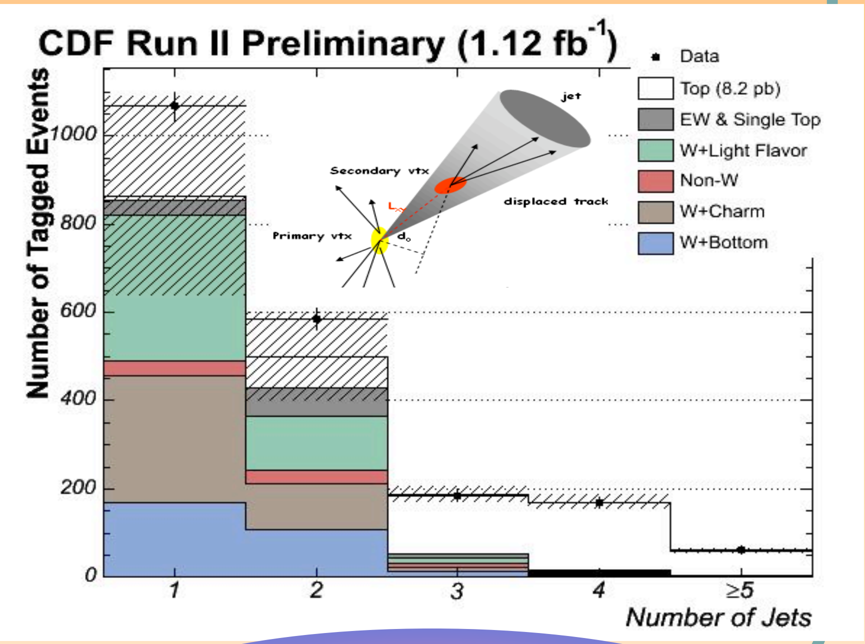
σ_{tt} = 6.2 ± 0.9 (stat) ± 0.8 (syst) ± 0.4 (lumi) pb

σ_{tt} = 6.2 ± 1.1 (stat) ± 0.7 (syst) ± 0.4 (lumi) pb

Lepton+jets cross section

- Signature: high-PT isolated e OR μ, missing E_T,
- DØ: ≥ 3 jets, separate events depending on # of b-tagged jets (displaced vertex), measure simultaneously with R = BR(t->Wb)/ BR(t->Wq)
- CDF: ≥ 3 jets, ≥ 1 b-tagged jet , $\Sigma\, p_T$ > 250 GeV



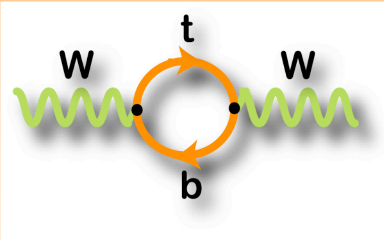


σ_{tt} = 8.1 ± 0.9 (stat+syst) ± 0.5 (lumi) pb
R > 0.812 @ 95% CL

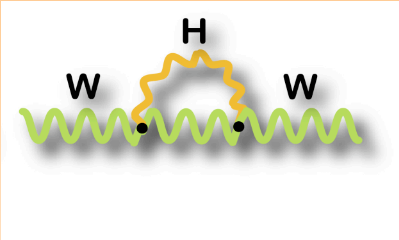
σ_{tt} = 8.5 ± 0.5 (stat)
± 0.8 (syst) ± 0.5 (lumi) pb

Top mass relation to Higgs

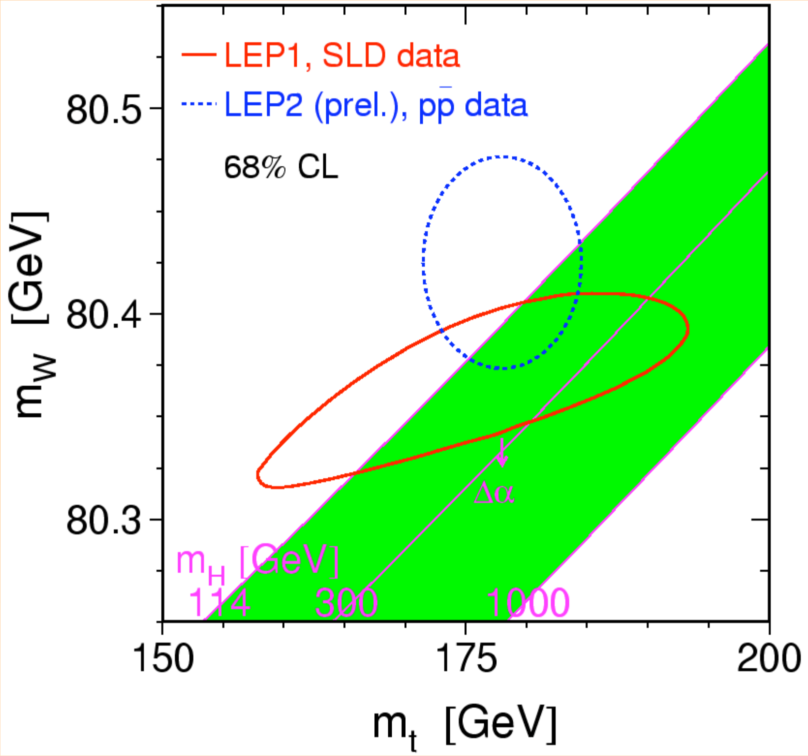
- Top quark mass is a fundamental parameter of SM
- Radiative corrections to SM predictions dominated by top mass
- Together with W mass places a constraint on Higgs mass



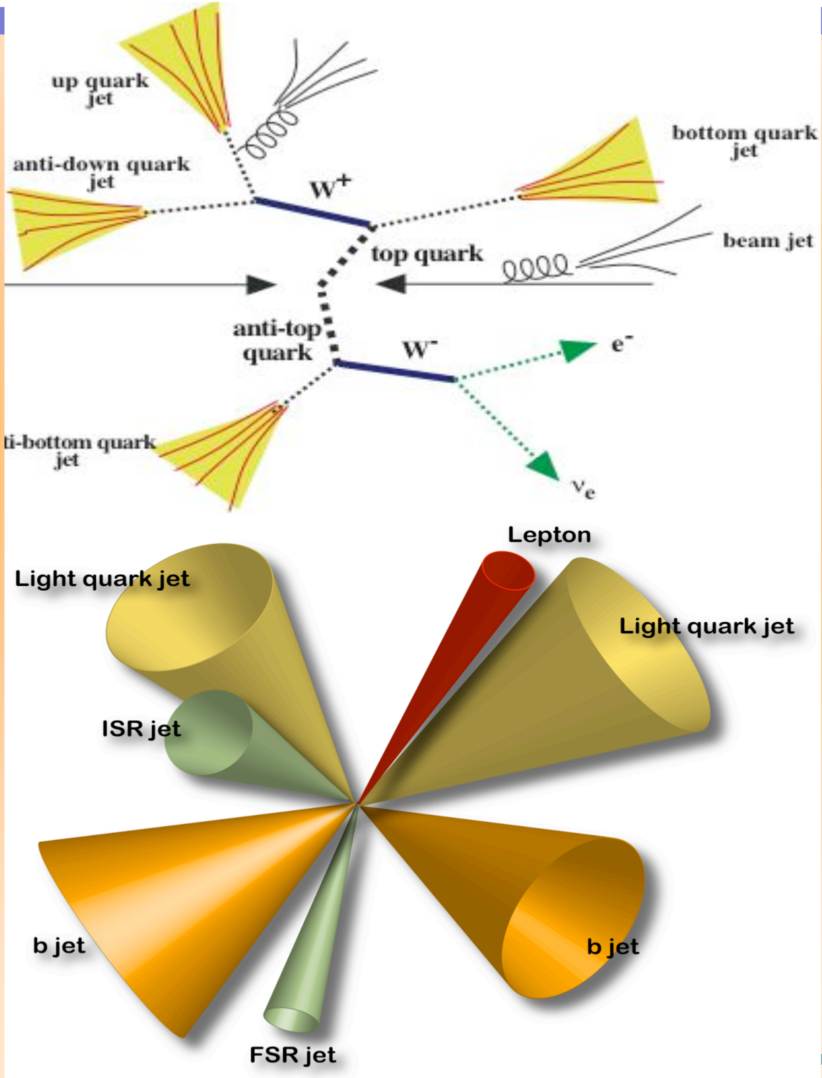
$$\Delta m_W \propto m_t^2$$



$$\Delta m_W \propto \ln m_H^2$$



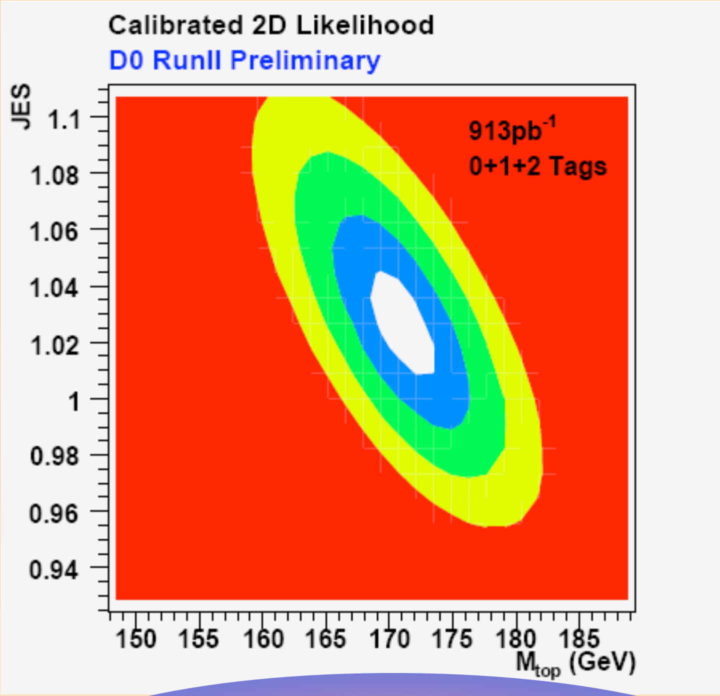
Top Mass Measurement

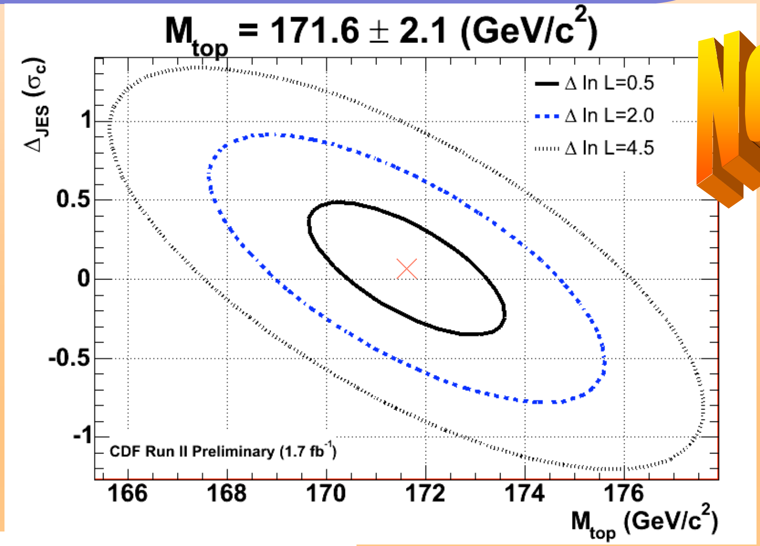


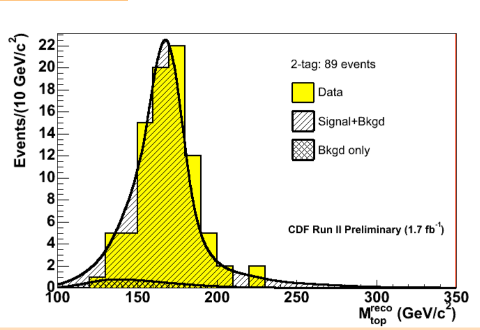
- **Kinematic reconstruction**
  - Use invariant mass constraints
    $m(jj) = m_W$, $m(\ell\upsilon) = m_W$, $m(\ell\upsilon b) = m(jjb)$
  - Match the jet to the correct parton
  - Extra jets spoil the picture
- **Energy Scale Calibration**
  - Reconstruction of the measured jet energies to the parton level
- **Sophisticated Analysis Techniques**
  - Kinematic fits, Matrix Elements, etc
- **Jet Energy Calibration in situ**
  - Simultaneous fit to invariant mass of W->jj
  - An internal constraint on the error of the jet energy scale
  - Reduces systematic uncertainty

Best Top Mass Results in Lepton+jets channel

- Exceeding original Run II expectations because of in-situ jet energy scale calibration



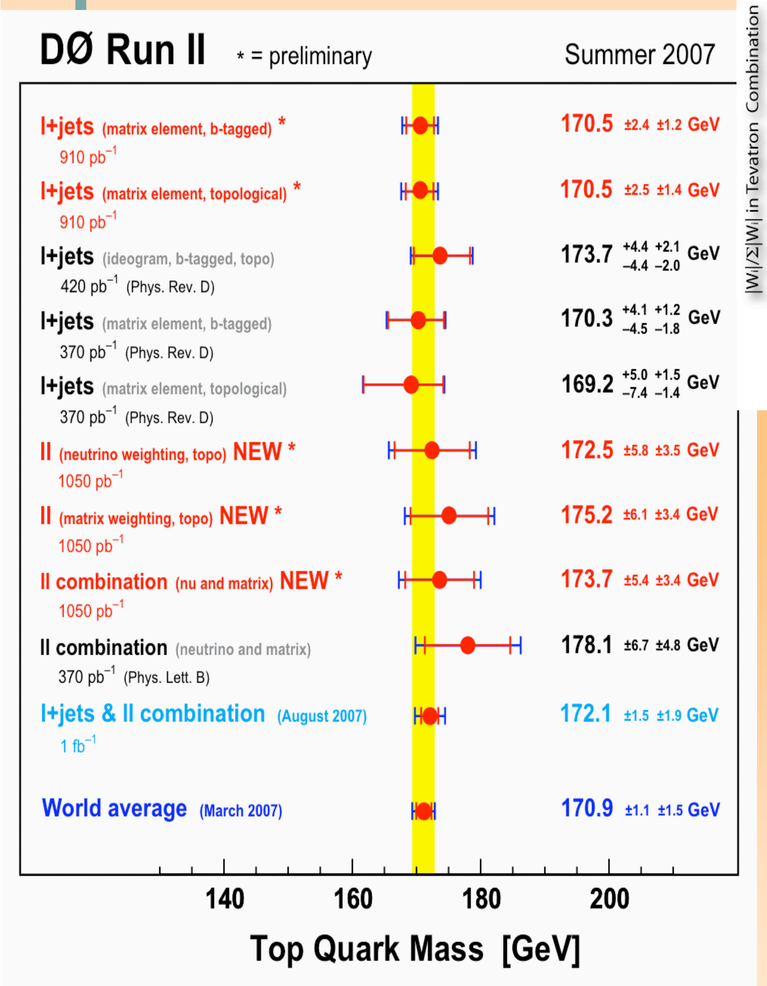


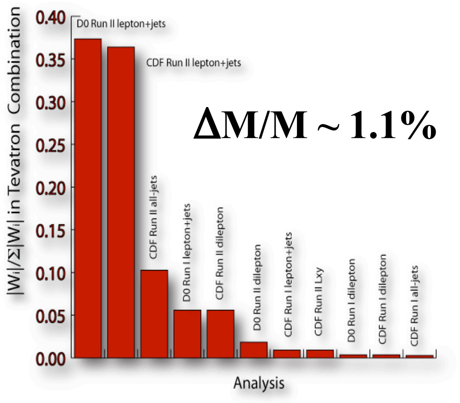


M_{top} = 170.5 ± 2.4 (stat+JES) ± 1.2 (syst) GeV

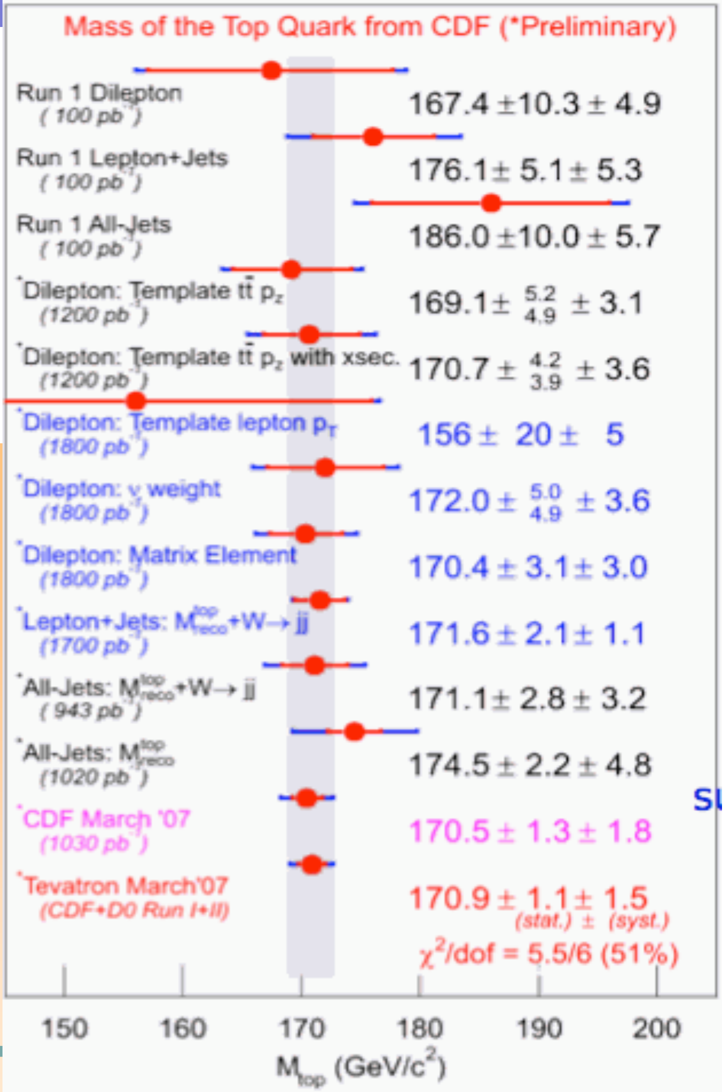
M_{top} = 171.6 ± 2.1 (stat+JES) ± 1.1 (syst) GeV

Top Mass Results



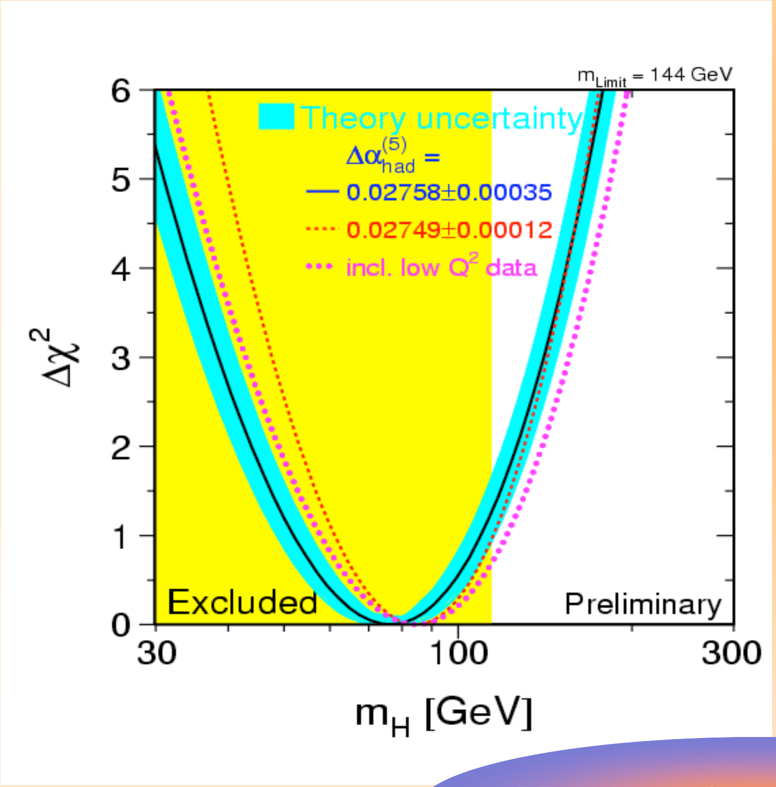


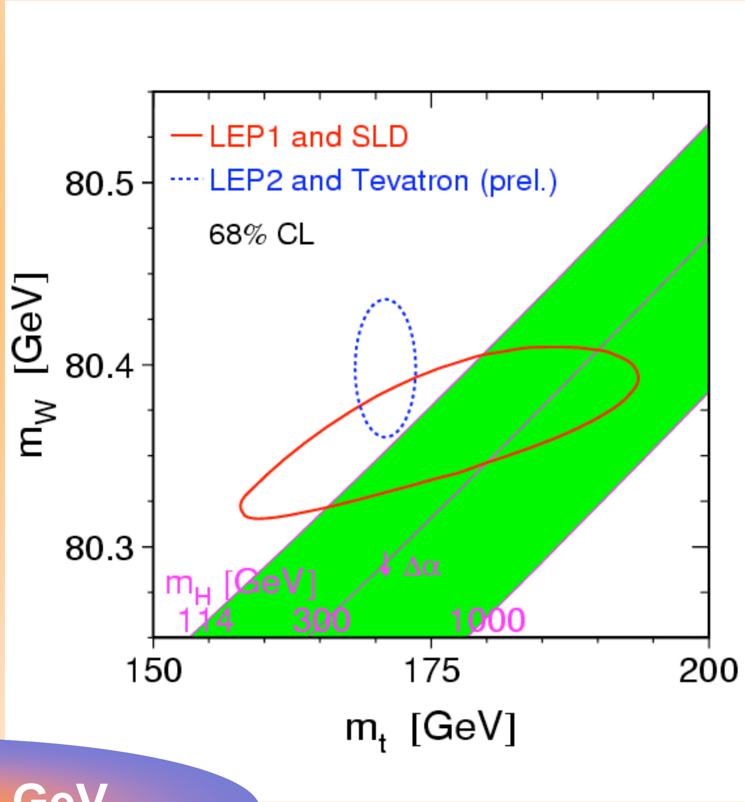
- Start addressing effects, too small to have an impact in first measurements
- Reconsider what theoretical aspects are relevant at 1 GeV level



Indirect bounds on the Higgs

- Latest measurements of top mass push the most likely value of the Higgs boson deeper into the excluded region

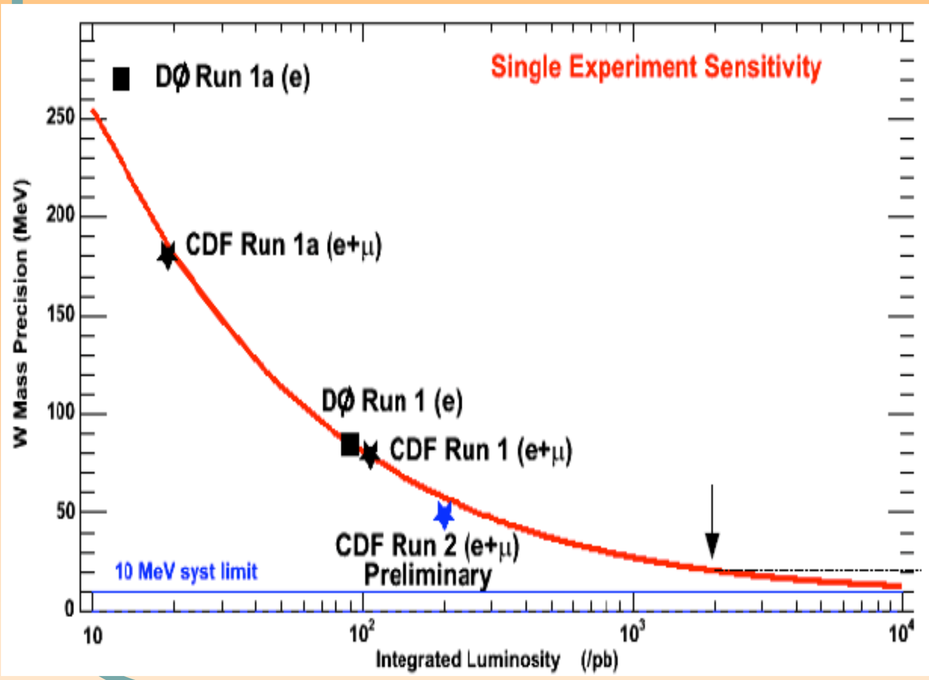


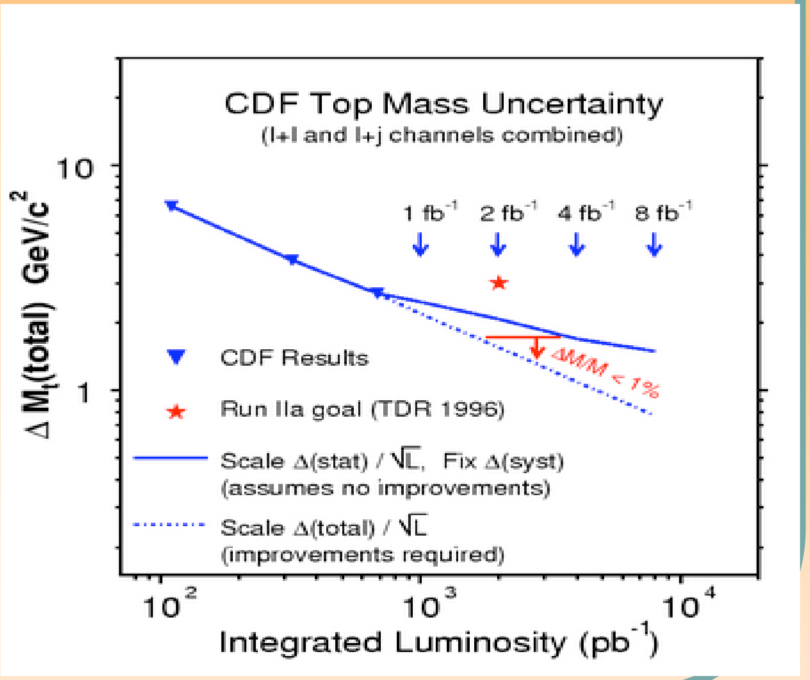


$M_{higgs} = 76.5^{+33}_{-24}$ GeV

Mass Measurements Prospects

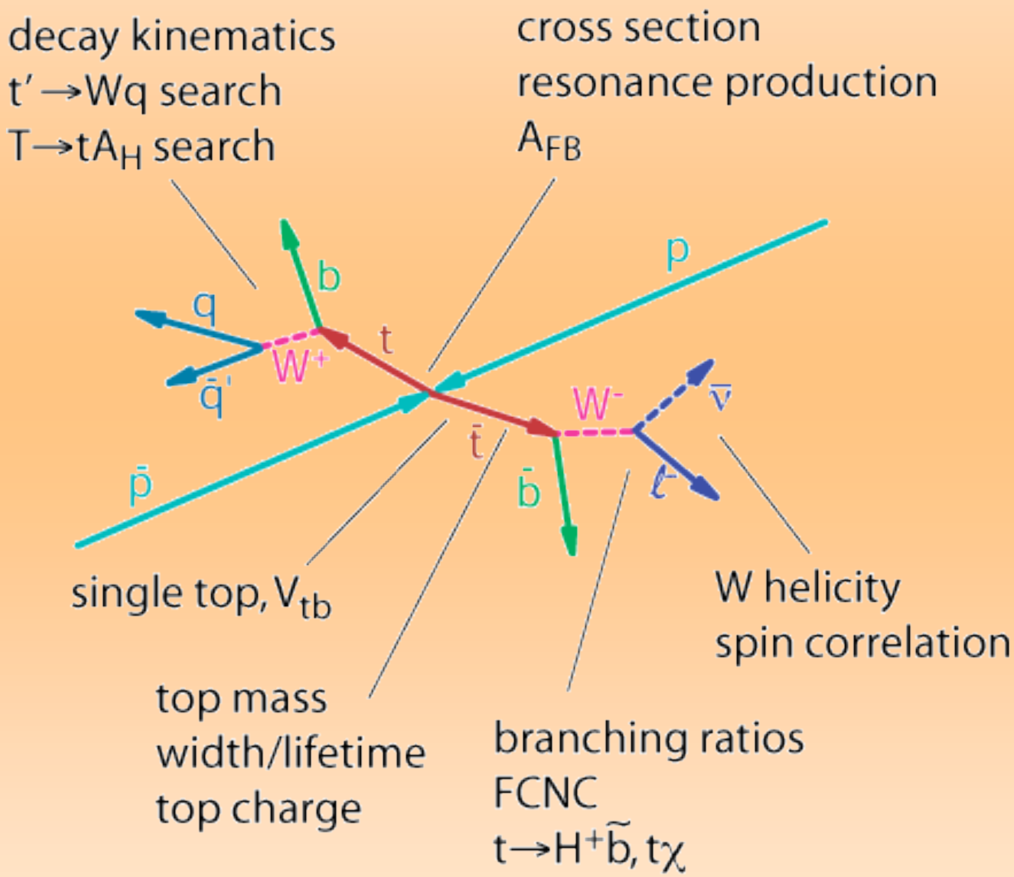
- Both for M_W and M_{top} Tevatron has done better than predicted
- Expect to get down to < 1 % uncertainty on top mass for CDF alone and ~1.0-1.2 GeV for CDF+DØ combined
- By the end of Run II W boson mass expected to be known with 20-25 MeV precision (0.02%)





Top Properties

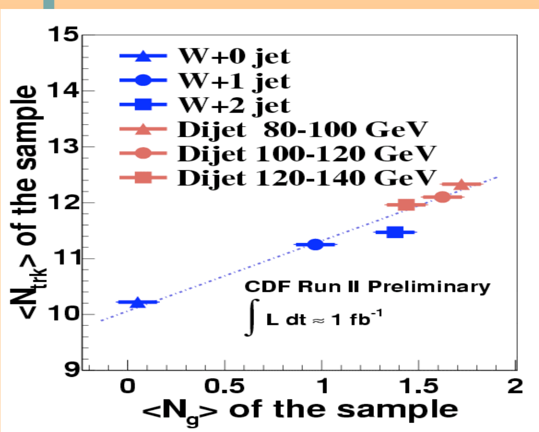
- Tevatron performs very rich top physics program
- Many top properties measurements just beginning to have sensitivity
- Lots about top still to understand!

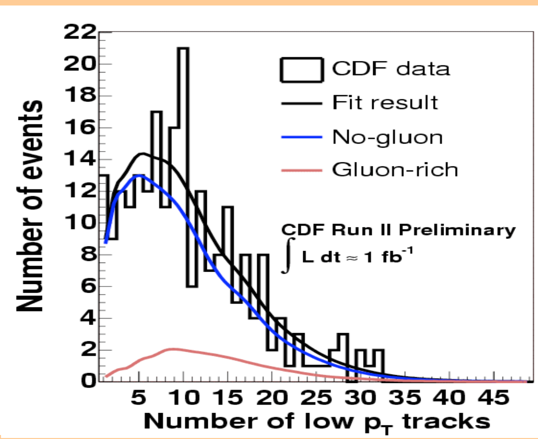


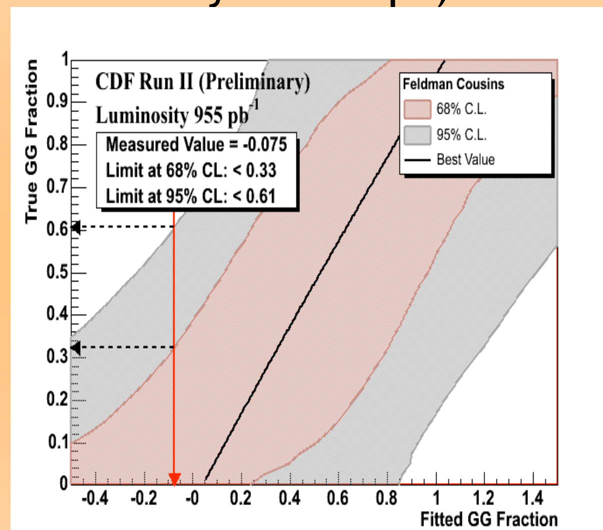
σ(gg→tt)/σ(pp →tt) Measurement

G. L. Kane and S. Mrenna
PRL 77: 3502-3505 (1996)

- Test of pQCD
- May reveal existence of unknown tt production and top quark decay mechanisms (top quark from gluino decays , and decays to stops)







- Make use of <Ntrk> (low-PT) vs <Ng> correlation
- Calibrate in W+jets and dijet data
- Fit W+jets b-tagged data to gluon-rich (dijet 80-100 GeV) and no gluon (W+0jet) components

σ(gg->tt)/σ(pp->tt) =0.07 ± 0.14(stat) ± 0.07(syst)

- gg (qq-bar) tt-bar events tend to be produced with unlike (like) spin.
- Use ANN to discriminate between both tt states and backgrounds
-

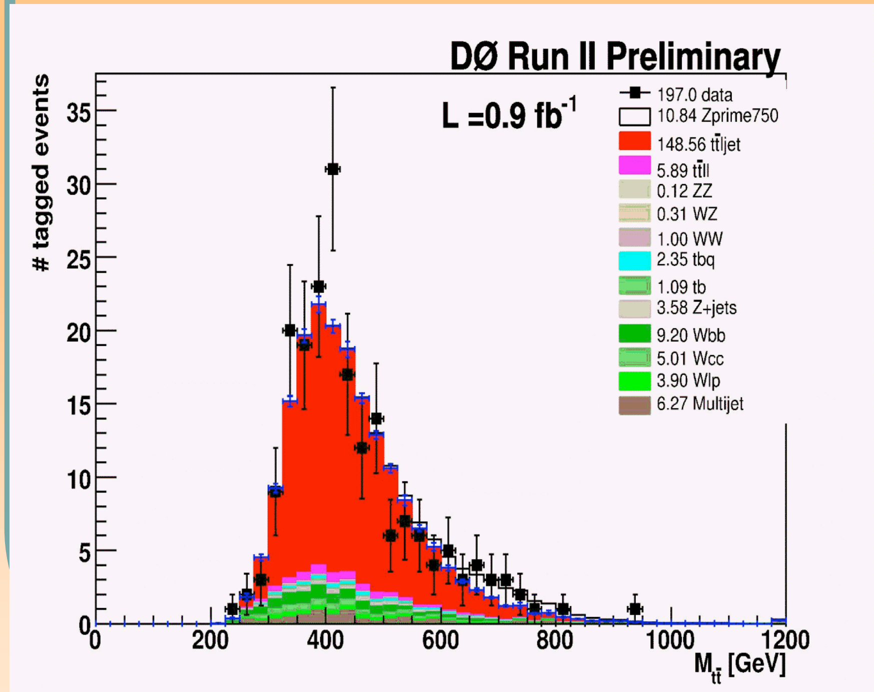
σ(gg->tt)/σ(pp->tt) < 0.61 @ 95%CL

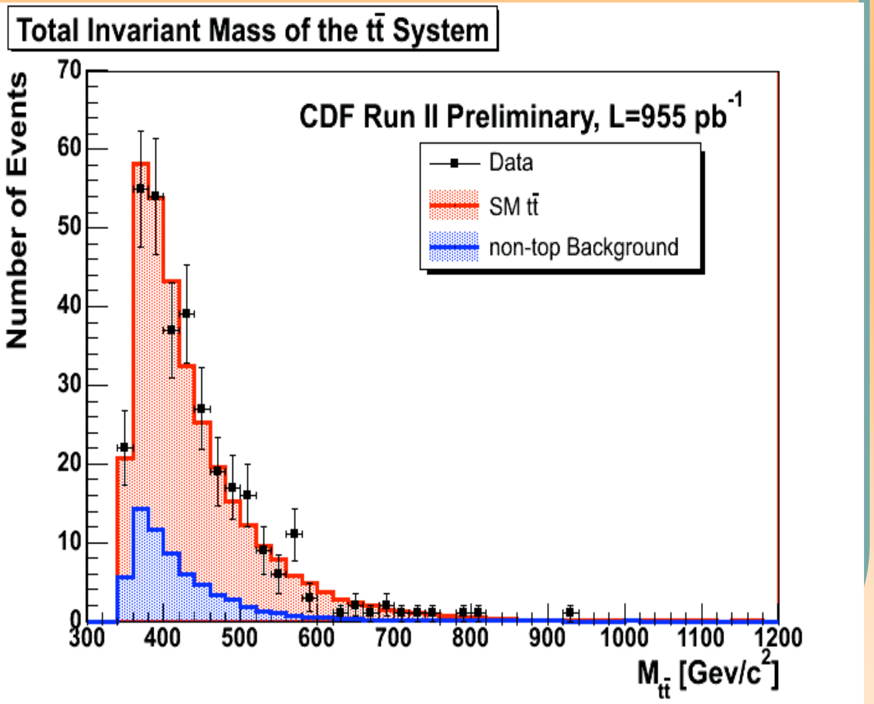
Search for Resonant Top Pair Production

- Resonant top pair production could arise of massive Z-like bosons (Topcolor-Assisted Technicolor) and other BSM theories

Hill, PRL B345, 483 (1995)
Hill and Parke, PRD49, 4454 (1994))

- No evidence for resonance observed
- Limits on masses of various exotic particles being set

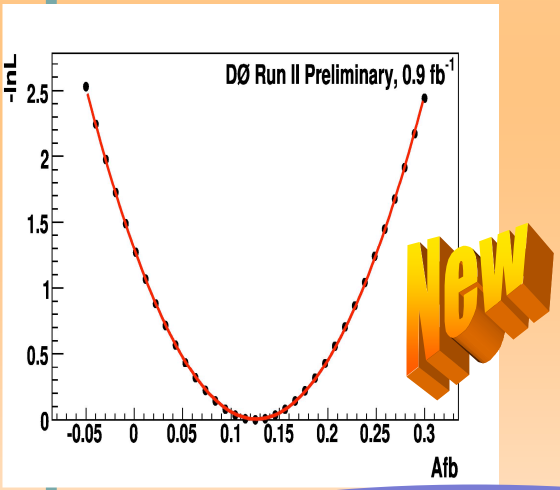




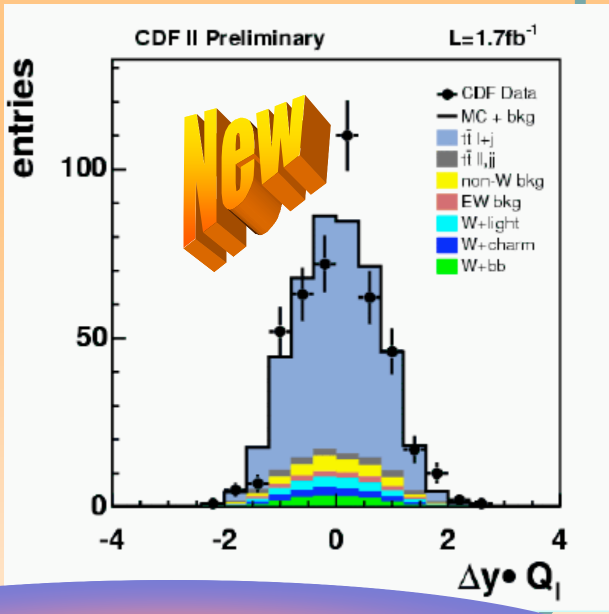
Forward-backward charge asymmetry in top pair production

J.Kühn et al.
PRL 81, 49 (1998),
PRD 59, 054017 (1999)

- NLO calculations predict forward-backward asymmetry of 4-6%
- Asymmetry arises from interference between contributions symmetric and antisymmetric under the exchange: top -> anti-top
- Top pairs in lepton + ≥ 4 jets channel are fully reconstructed
- Make use of Lorentz-invariant rapidity difference of top and anti-top times the lepton charge: $\Delta y \cdot Q_l$ variable



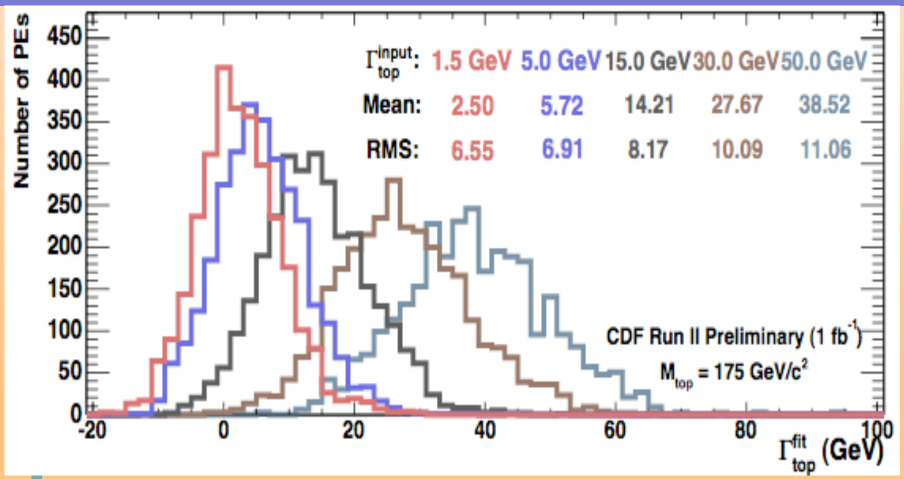
- Numbers of events measured in two bins: positive and negative values of $\Delta y \cdot Q_l$
- CDF: The asymmetry value is background subtracted and corrected for smearing effects of ttbar pair reconstruction with the inversion of 2x2 matrix

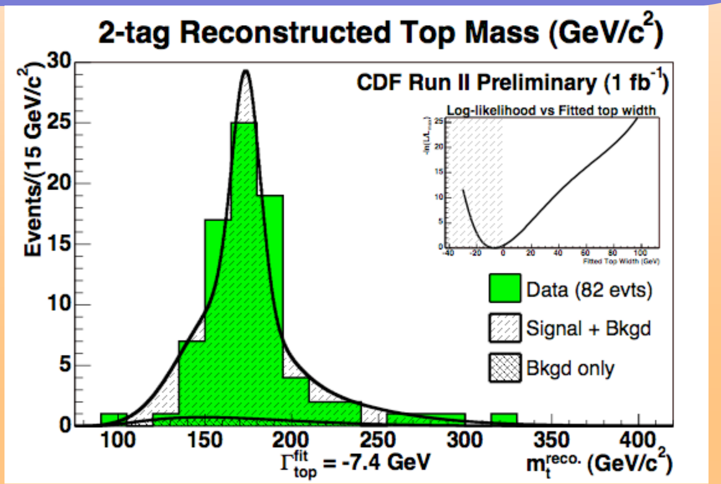


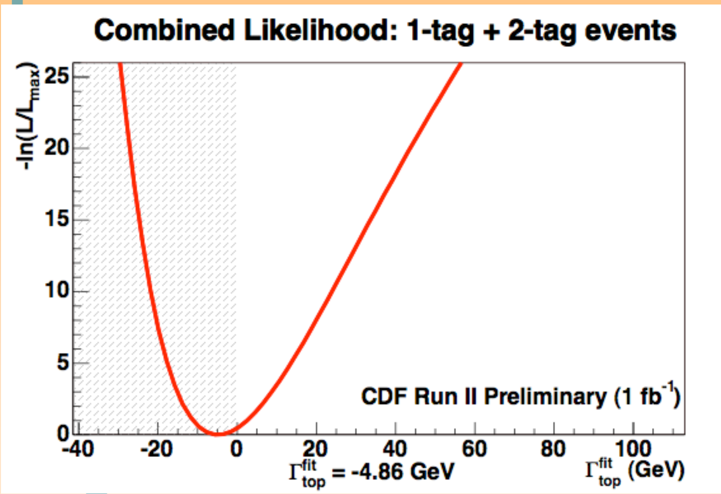
A_{fb}[DØ] = 12 ± 8(stat) ± 1(syst) %
(not corrected for acceptance and reconstruction effects)

A_{fb}[CDF] = 28 ±13(stat) ±5(syst) %

Top Quark Width







- Compare top mass distributions to Monte Carlo with various input width
- Use Feldman-Cousins prescriptions for setting the limit

First direct measurement of top width in Run2

Γ_t < 12.7 @ 95% CL
(for Mt = 175 GeV)

Top Charge

- Is the top the SM particle with Q=+2/3 or an exotic quark Q=-4/3?

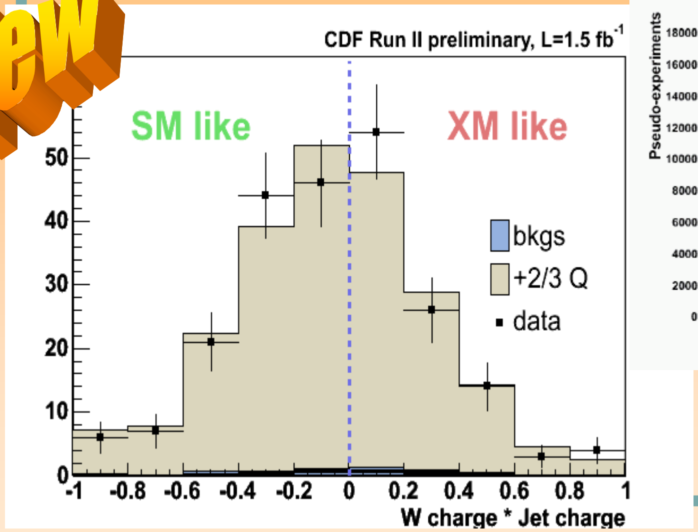
**D. Chang et al.
PRD 59, 091503**

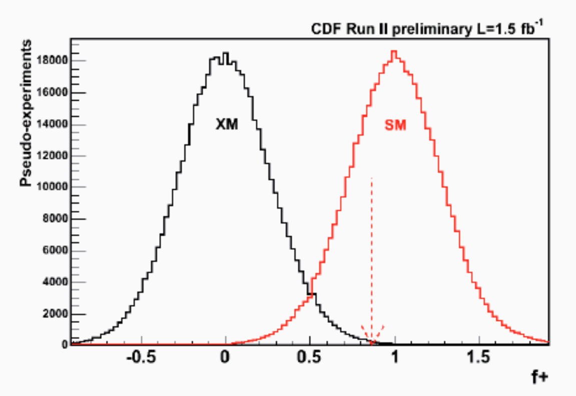
- Select and fully reconstruct top events in lepton+jets (2 b-tagged jets) and dilepton channel (≥1 tagged jet)
- Determine:
  - ➔ flavor of b-jet
  - ➔ charge of W (lepton)
  - ➔ pairing between W and b (χ^2 fit and M_{lb})

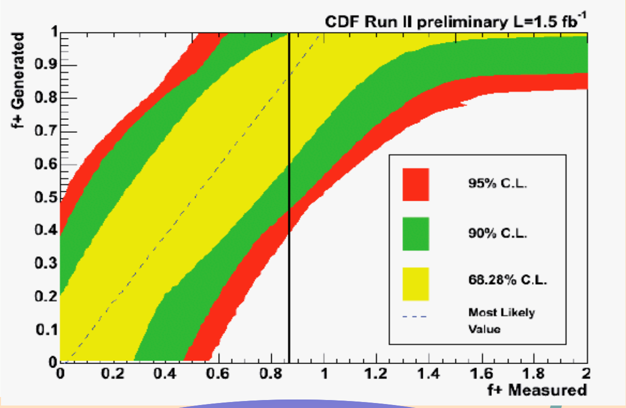
$$\mathrm{JetQ} = \frac{\sum (\vec{p}_{track} \bullet \vec{p}_{jet})^x \cdot Q_{track}}{\sum (\vec{p}_{track} \bullet \vec{p}_{jet})^x}$$

- Optimized to increase the signal purity
- Calibrated in a data sample of di-jet events

New





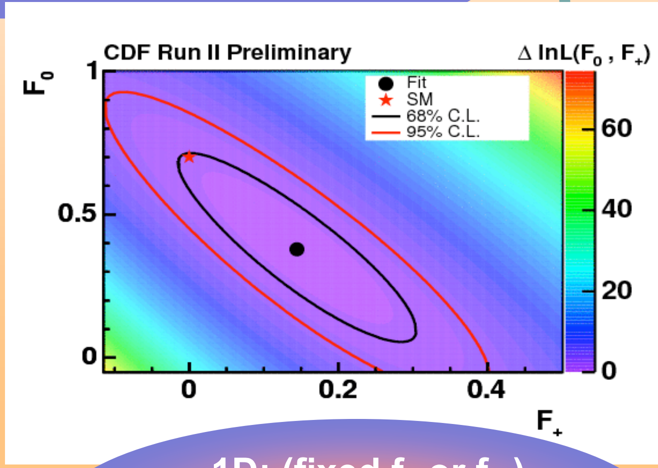


XM excluded with CL = 87%

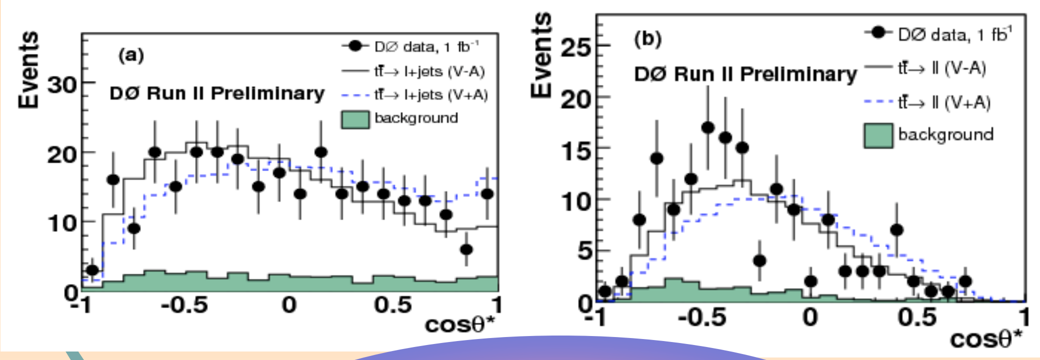
$f_+ > 0.4$ @ 95%CL

W Helicity

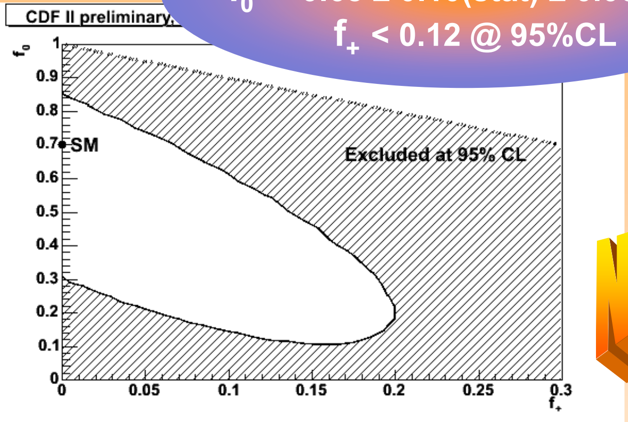
- Test of the V-A structure of tWb vertex: $\frac{-ig}{2\sqrt{2}}\bar{t}\gamma^{\mu}(1-\gamma^{5})V_{tb}bW_{\mu}$
- SM prediction:
  - f_- ~30% -left-handed; f_0 ~ 70% - longitudinal; f_+ ~ 0.036% - right-handed
- CDF: lepton+≥ 4 jets (≥ 1 tag) events
  - Two techniques: different event reconstruction and b-tagging algorithm
- DØ: add di-lepton channel, no b-tagging
- Measure angular distribution of charged lepton wrt top in W rest frame: $\cos\theta^*$
- Fit helicity fractions with unbinned likelihood



1D: (fixed f_0 or f_+)
f_0 = 0.65 ± 0.10(stat) ± 0.06(syst)
f_+ < 0.12 @ 95%CL



1D: (fixed f_0)
f_+ = 0.017 ± 0.048(stat) ± 0.047(syst)
f_+ < 0.14 @ 95%CL

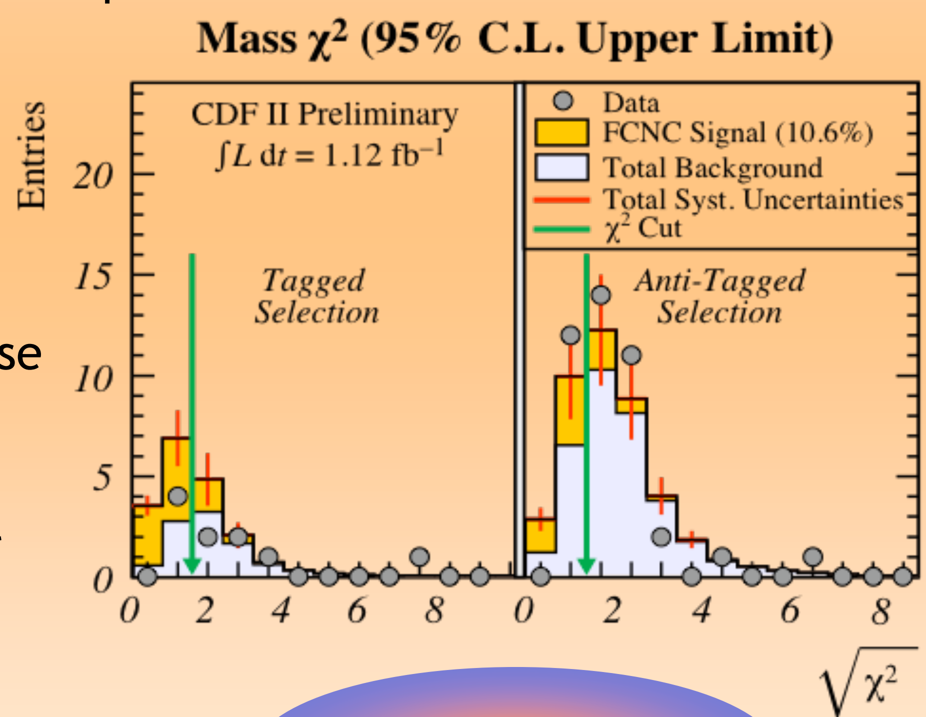


New

1D: (fixed f_0 or f_+)
f_0 = 0.57 ± 0.11(stat) ± 0.04(syst)
f_+ < 0.07 @ 95%CL

Search for FCNC t->Zq

- FCNC are rare in the Standard Model
- Within the SM:
  - BR(t->Zq) = O(10^{-14})
- Beyond the SM predicted can be up to O(10^{-2})
- Signature: tt-> ZqWb->llqqqb
- Dominant background: Z+jets
- Blind search in Z + ≥ 4 jets channel
- Use 2 signal regions to increase sensitivity: 1 loose tag and anti-tag
- Use χ^2 from the kinematic fit
- New limit surpasses the LEP limit



BR(t->Zq) < 10.6% @ 95%CL

Conclusions

- Tevatron experiments have in hands 2 fb^{-1} of data and produce plenty of physics results
- Aiming for 6-8 fb^{-1} of data by 2009 with two well understood detectors and continuously improving accelerator performance
- Tests of the Standard Model are performed at the level of precision, which meets or surpasses that of LEP
- Valuable constraints within SM e.g. PDFs, NNLO QCD will come with final datasets
- Fed into Top/W Mass measurement improvements - Constraints on Higgs Mass
  - Top Mass Precision = 1.1% => ~ 0.7% by the end of Run II
  - W Mass Precision = 0.04% => ~ 0.02% by the end of Run II

- The Higgs boson hunt is under way
- New Physics might be around the corner!